GFSSP Training Course

Afternoon Session

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University of Alabama in Huntsville
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GFSSP - Advanced

- Mathematical Formulation
  - Conjugate Heat Transfer
  - Advanced Applications
- User Subroutine
- Data Structure
- Break
- Advanced Modeling Options
  - Pressurization & Control Valve
  - Pressure Regulator & Flow Regulator
- Tutorial on Pressurization & Control Valve
- Tutorial on Chilldown of Cryogenic Transfer Line

MATHEMATICAL FORMULATION
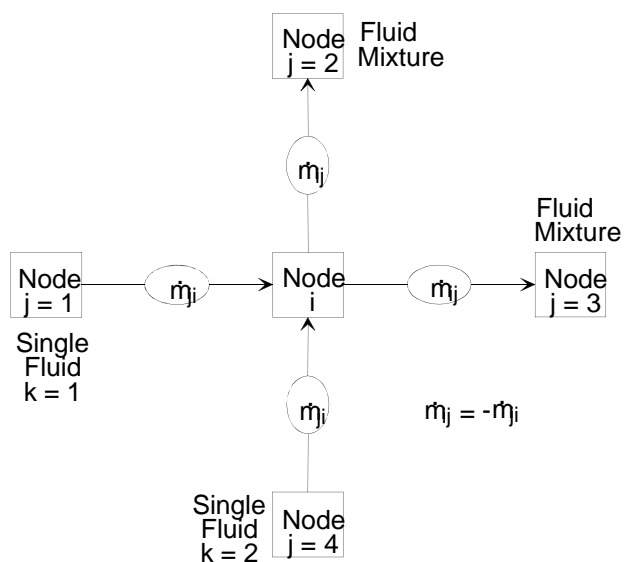
Content

- Mathematical Closure
- Governing Equations
- Solution Procedure

MATHEMATICAL CLOSURE
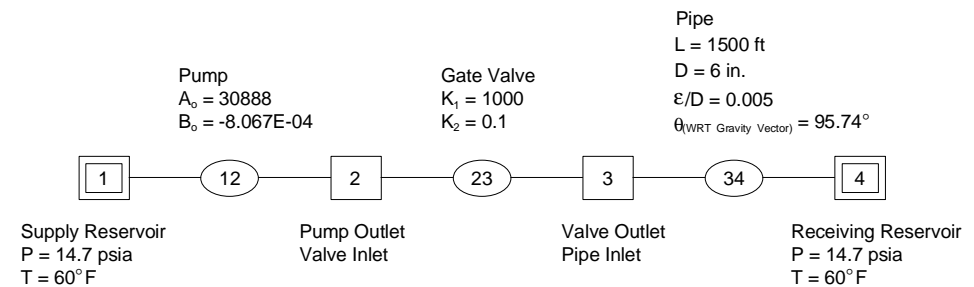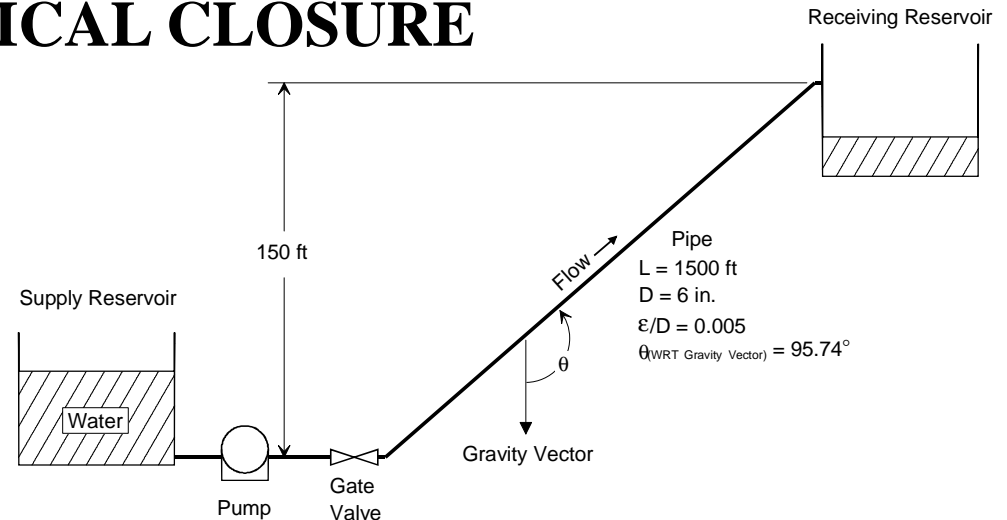
Problem of a Steady State Flow Network

• **Given** : Pressures and Temperatures at Boundary Nodes

• **Find** : Pressures and Temperatures at Internal Nodes and Flowrates in Branches
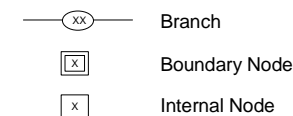
Primary Variables

$$p_2, p_3, T_2, T_3, \dot{m}_{12}, \dot{m}_{23}, \dot{m}_{34}$$

Secondary Variables

$$\rho_2, \rho_3, \mu_2, \mu_3$$

Receiving Reservoir

150 ft

Supply Reservoir

Flow

Pipe
L = 1500 ft
D = 6 in.
ε/D = 0.005
θ(WRT Gravity Vector) = 95.74°

θ

Water

Gravity Vector

Pump

Gate Valve

Pump
A_o = 30888
B_o = -8.067E-04

Gate Valve
K_1 = 1000
K_2 = 0.1

Pipe
L = 1500 ft
D = 6 in.
ε/D = 0.005
θ(WRT Gravity Vector) = 95.74°

| 1 | — 12 — | 2 | — 23 — | 3 | — 34 — | 4 |

Supply Reservoir
P = 14.7 psia
T = 60°F

Pump Outlet
Valve Inlet

Valve Outlet
Pipe Inlet

Receiving Reservoir
P = 14.7 psia
T = 60°F

Legend

—(xx)— Branch

[X] Boundary Node

[x] Internal Node

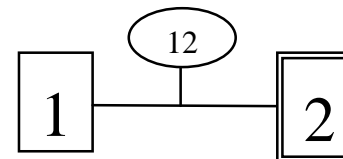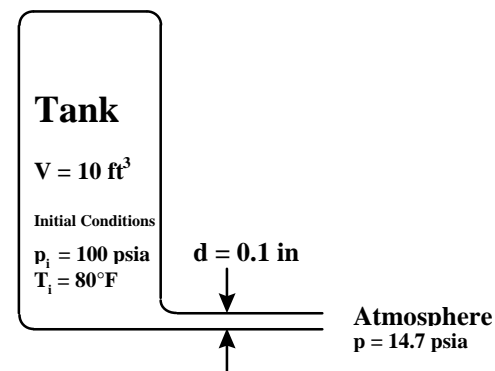# MATHEMATICAL CLOSURE

Problem of an Unsteady Flow Network

• **Given** : Pressures and Temperatures at Boundary Nodes and Initial Values at Internal Nodes

• **Find** : Pressures and Temperatures at Internal Nodes and Flowrates in Branches with Time.

Primary Variables

$$p_1(\tau), T_1(\tau), m_1(\tau), \dot{m}(\tau)$$

Secondary Variables

$$\rho_1(\tau), \ \mu_1(\tau)$$

Tank

V = 10 ft^3

Initial Conditions

p_i = 100 psia   **d = 0.1 in**
T_i = 80°F

Atmosphere
p = 14.7 psia

1 — 12 — 2

MATHEMATICAL CLOSURE

Principal Variables:

Unknown Variable	Available Equations to Solve
1. Pressure	1. Mass Conservation Equation
2. Flowrate	2. Momentum Conservation Equation
3. Temperature	3. Energy Conservation Equation
4. Specie Concentrations (Mixture)	4. Conservation Equations for Mass Fraction of Species
5. Mass (Unsteady)	5. Thermodynamic Equation of State

MATHEMATICAL CLOSURE

Secondary Variables:

Thermodynamic & Thermophysical Properties

Unknown Variable	Available Equations to Solve
Density	
Specific Heats	Equilibrium Thermodynamic Relations
Viscosity	[GASP, WASP & GASPAK Property Programs]
Thermal Conductivity	

Flow Resistance

Unknown Variable	Available Equations to Solve
1. Friction Factor	1. Empirical Relations
2. Loss Coefficient	2. User Specified

GOVERNING EQUATIONS

- Mass Conservation

- Momentum Conservation

- Energy Conservation

- Fluid Species Conservation

- Equation of State

- Mixture Property

Coupling of Thermodynamics & Fluid Dynamics

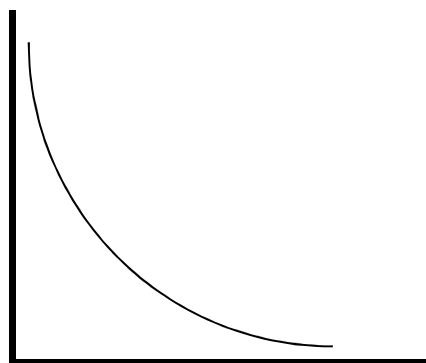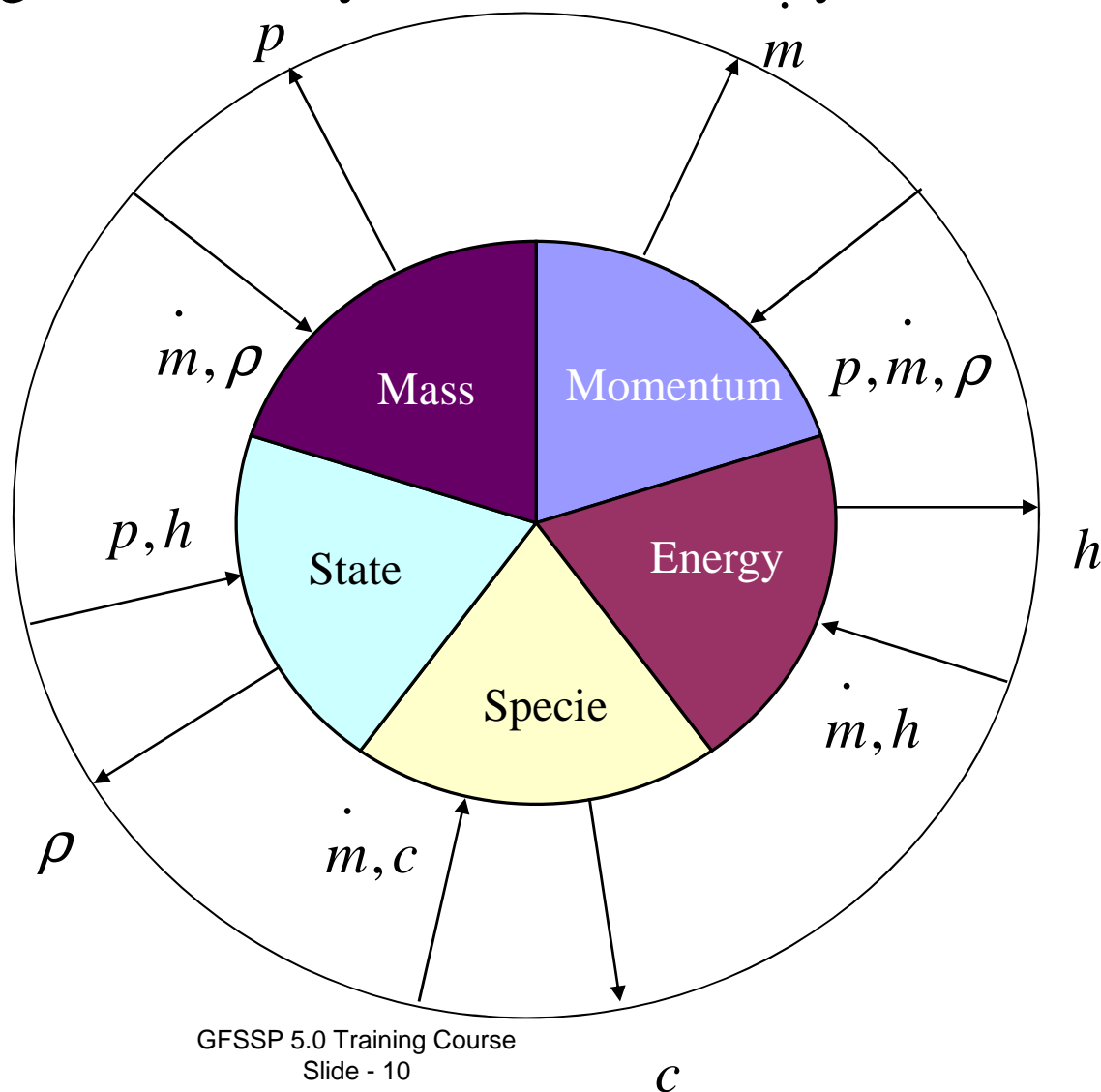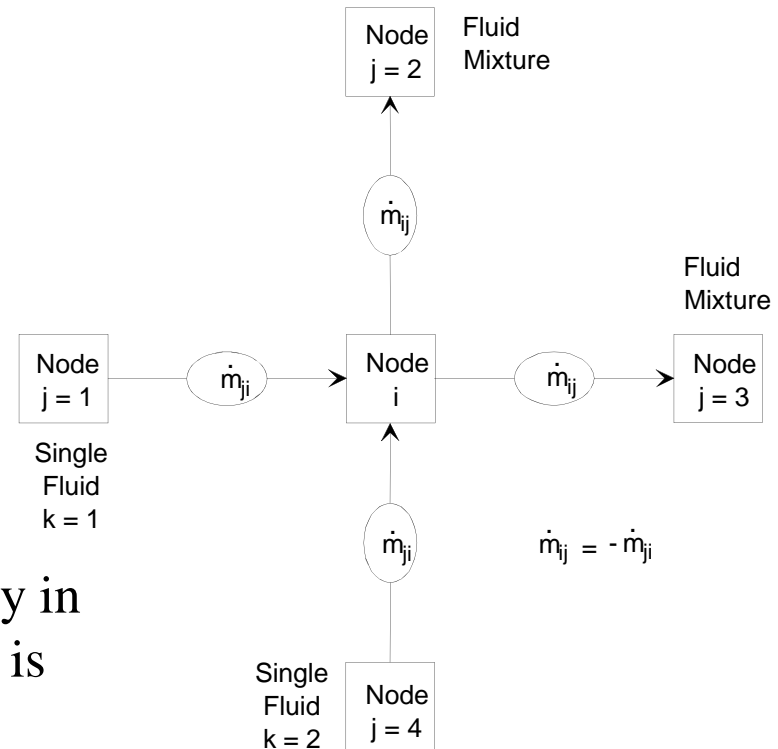# GOVERNING EQUATIONS

MASS CONSERVATION EQUATION

$$\frac{m_{\tau+\Delta\tau} - m_\tau}{\Delta\tau} = \sum_{j=1}^{j=n} \dot{m}_{ij}$$

Note : Pressure does not appear explicitly in Mass Conservation Equation although it is earmarked for calculating pressures

GOVERNING EQUATIONS

MOMENTUM CONSERVATION EQUATION

- Represents Newton's Second Law of Motion

Mass $_X$ Acceleration   =   Forces

- Unsteady

- Longitudinal Inertia

- Transverse Inertia

- Pressure

- Gravity

- Friction

- Centrifugal

- Shear Stress

- Moving Boundary

- Normal Stress

- External Force
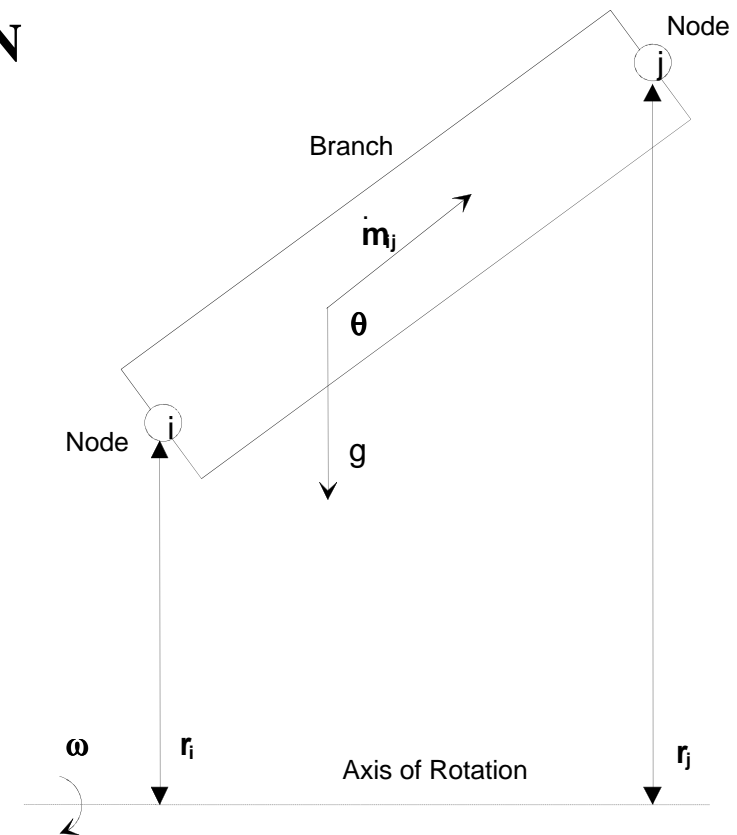
MOMENTUM CONSERVATION EQUATION

Mass ₓ Acceleration Terms in GFSSP

$$\dot{m}_{ij}$$

$$u_u \qquad u_{ij}$$

Unsteady

$$\frac{\left(mu_{ij}\right)_{\tau+\Delta\tau} - \left(mu_{ij}\right)_{\tau}}{g_c \Delta\tau}$$

Longitudinal Inertia

$$MAX\left|\dot{m}_{ij},0\right|\left(u_{ij}-u_u\right) - MAX\left|-\dot{m}_{ij},0\right|\left(u_{ij}-u_u\right)$$
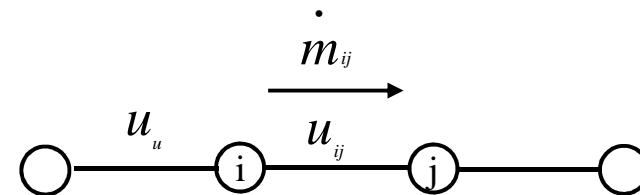
MOMENTUM CONSERVATION EQUATION

Force Terms in GFSSP
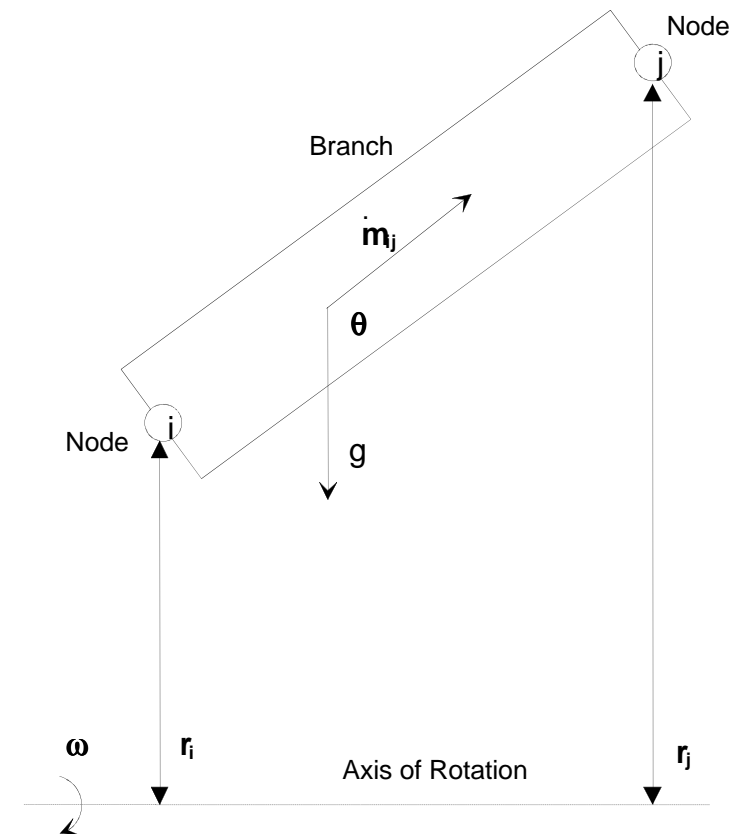
Pressure

$$(p_i - p_j)A_{ij}$$

Gravity

$$\frac{\rho g V Cos\,\theta}{g_c}$$

Friction

$$-K_f\,\dot{m}_{ij}\left|\dot{m}_{ij}\right|A_{ij}$$

Centrifugal

$$\frac{\rho\,K_{rot}^2\,\omega^2\,A}{g_c}$$

Node

j

Branch

$\dot{\mathbf{m}}_{ij}$

θ

Node

i

g

ω $\mathbf{r_i}$ Axis of Rotation $\mathbf{r_j}$

GOVERNING EQUATIONS

ENERGY CONSERVATION EQUATION

• Energy Conservation Equation can be written in Enthalpy or Entropy

  • Based on Upwind Scheme

Enthalpy Equation

Rate of Increase of Internal Energy =

Enthalpy Inflow - Enthalpy Outflow + Heat Source

$$\frac{m\left(h - \dfrac{p}{\rho J}\right)_{\tau + \Delta\tau} - m\left(h - \dfrac{p}{\rho J}\right)_{\tau}}{\Delta\tau} = \sum_{j=1}^{j=n}\left\{ MAX\left[-\dot{m}_{ij}, 0\right]h_j - MAX\left[\dot{m}_{ij}, 0\right]h_i \right\} + Q_i$$
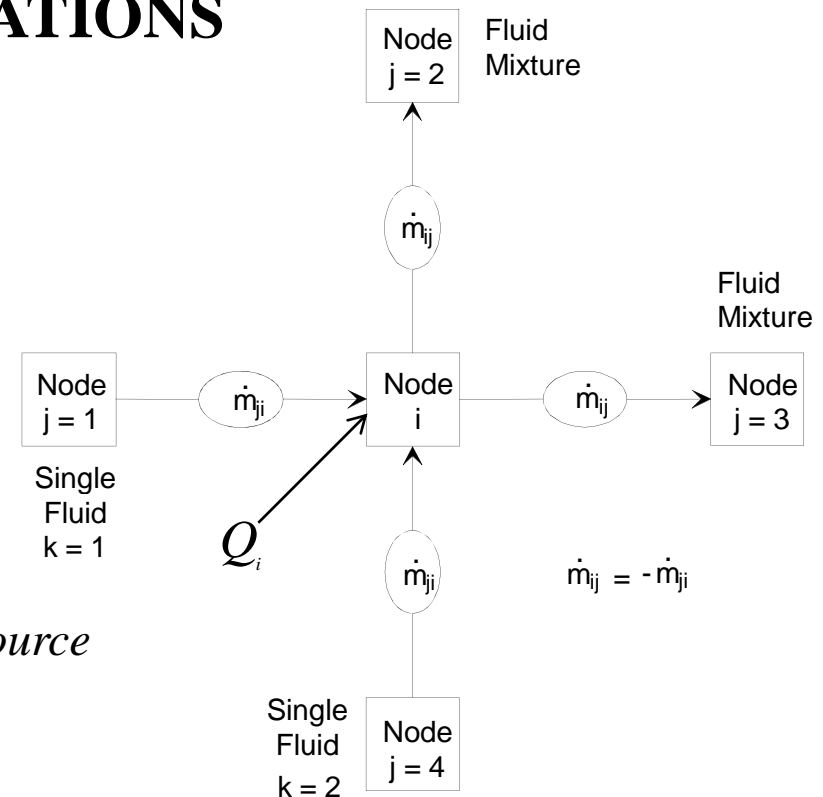
GOVERNING EQUATIONS

ENERGY CONSERVATION EQUATION

Entropy Equation

Rate of Increase of Entropy =

Entropy Inflow - Entropy Outflow +

Entropy Generation + Entropy Source
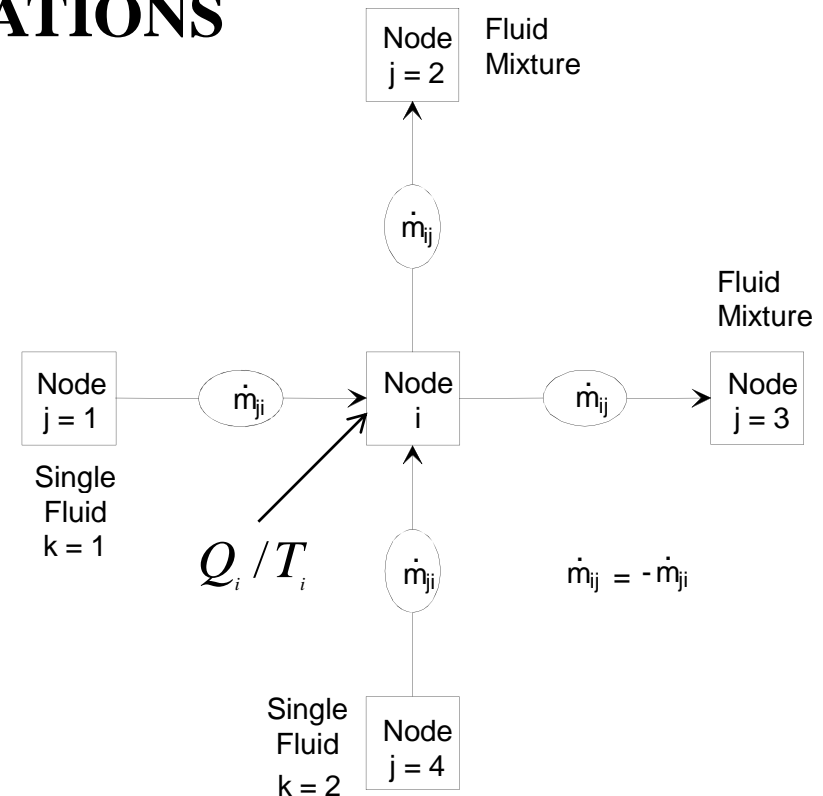
$$\frac{(ms)_{\tau+\Delta\tau}-(ms)_\tau}{\Delta\tau}=\sum_{j=1}^{j=n}\left\{MAX\left[-\dot{m}_{ij},0\right]s_j-MAX\left[\dot{m}_{ij},0\right]s_i\right\}+\sum_{j=1}^{j=n}\left\{\frac{MAX\left[-\dot{m}_{ij},0\right]}{|\dot{m}_{ij}|}\right\}\dot{S}_{ij,gen}+\frac{Q_i}{T_i}$$

GOVERNING EQUATIONS

FLUID SPECIE CONSERVATION EQUATION

Node j = 2 — Fluid Mixture

$\dot{m}_{ij}$

Fluid Mixture

Rate of Increase of Fluid Specie =

Fluid Specie Inflow - Fluid Specie Outflow +

Fluid Specie Source

Node j = 1 — $\dot{m}_{ji}$ → Node i → $\dot{m}_{ij}$ → Node j = 3

Single Fluid k = 1

$S_{i,k}$ $\dot{m}_{ji}$ $\dot{m}_{ij} = -\dot{m}_{ji}$

Single Fluid k = 2 — Node j = 4
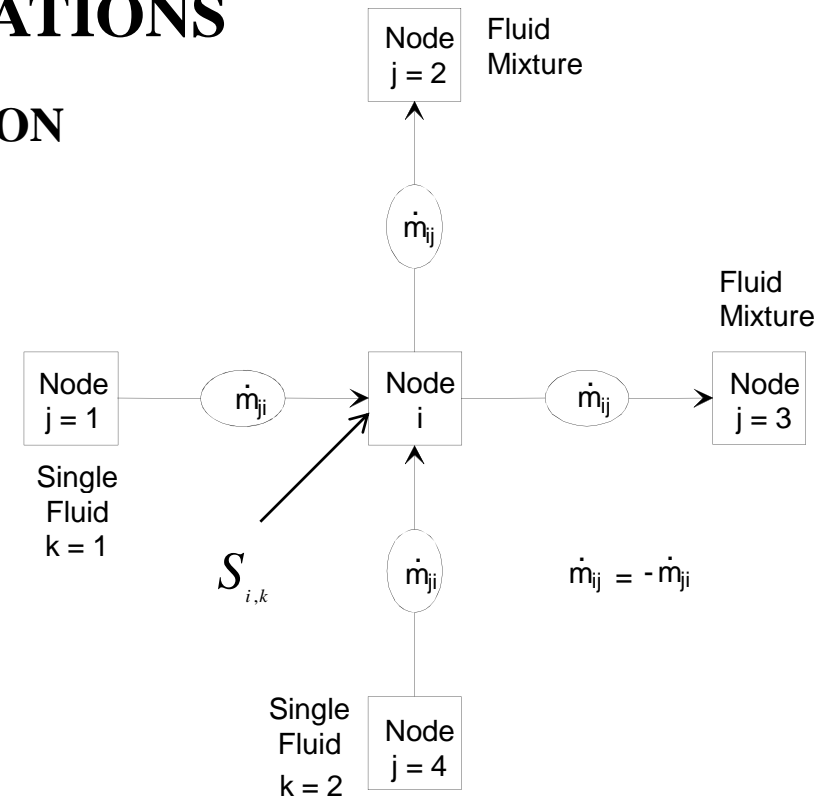
$$\frac{(m_i c_{i,k})_{\tau+\Delta\tau} - (m_i c_{i,k})_{\tau}}{\Delta\tau} = \sum_{j=1}^{j=n}\left\{ MAX\left[-\dot{m}_{ij},0\right]c_{j,k} - MAX\left[\dot{m}_{ij},0\right]c_{i,k}\right\} + \dot{S}_{i,k}$$

GOVERNING EQUATIONS

EQUATION OF STATE

For unsteady flow, resident mass in a control volume is calculated

from the equation of state for a real fluid

$$m = \frac{pV}{RTz}$$

Z is the compressibility factor determined from

higher order equation of state

GOVERNING EQUATIONS

EQUATION OF STATE

- GFSSP uses two separate Thermodynamic Property Packages

    GASP/WASP and GASPAK

- GASP/WASP uses modified Benedict, Webb & Rubin (BWR)

    Equation of State

- GASPAK uses "standard reference" equation from

    - National Institute of Standards and Technology (NIST)

    - International Union of Pure & Applied Chemistry (IUPAC)

    - National Standard Reference Data Service of the USSR

GOVERNING EQUATIONS

Mixture Property Relation

<u>Density</u>

• Calculated from Equation of State of Mixture with Compressibility Factor

$$\rho_i = \frac{p_i}{z_i R_i T_i} \qquad\qquad R_i = \sum_{k=1}^{k=n} x_k R_k$$

• Compressibility Factor of Mixture is Mole average of Individual Components

$$z_i = \sum_{k=1}^{k=n} x_k z_k \qquad\qquad z_k = \frac{p_i}{\rho_k R_k T_k}$$

GOVERNING EQUATIONS

Mixture Property Relation

<u>Thermophysical Properties</u>

• Viscosity, Specific Heat and Specific Heat Ratios are calculated

 by taking Molar Average

$$\mu_i = \sum_{k=1}^{k=n} x_k \mu_k \qquad\qquad \gamma_i = \sum_{k=1}^{k=n} x_k \gamma_k$$

$$C_{p,i} = \sum_{k=1}^{k=n} \frac{C_{p,k} x_k M_k}{x_k M_k}$$

GOVERNING EQUATIONS

Mixture Property Relation

<u>Temperature</u>

• Mixture Temperature is calculated from Energy Conservation Equation

$$
(T_i)_{\tau+\Delta\tau} = \frac{\sum_{j=1}^{j=n}\sum_{k=1}^{k=nf}\mathrm{Cp}_k\, x_k\, T_j\, MAX\left[-\dot{m}_{ij},0\right]+\left(C_{p,i}\, m_i\, T_i\right)_\tau/\Delta\tau + Q_i}{\sum_{j=1}^{j=n}\sum_{k=1}^{k=nf}\mathrm{Cp}_k\, x_k\, MAX\left[\dot{m}_{ij},0\right]+\left(C_{p,i}\, m\right)_\tau/\Delta\tau}
$$

<u>Limitation</u>

• Cannot handle phase change of mixture

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GOVERNING EQUATIONS
Summary

- Familiarity with GFSSP's Governing Equations is not absolutely necessary to use the code

- However, working knowledge about Governing Equations is helpful to implement various options in a complex flow network

- A good understanding of Governing Equations is necessary to introduce new physics in the code

SOLUTION PROCEDURE

- Successive Substitution

- Newton-Raphson

- Simultaneous Adjustment with Successive Substitution (SASS)

- Convergence

SOLUTION PROCEDURE

- Non linear Algebraic Equations are solved by
    - Successive Substitution
    - Newton-Raphson

- GFSSP uses a Hybrid Method
    - SASS (Simultaneous Adjustment with Successive Substitution)
    - This method is a combination of Successive Substitution and Newton-Raphson

SOLUTION PROCEDURE

SUCCESSIVE SUBSTITUTION METHOD

STEPS:

1. Guess a solution for each variable in the system of equations
2. Express each equation such that each variable is expressed in terms of other variables: e. g. X = f (Y,Z) and Y = f (X,Z) etc
3. Solve for each variable
4. Under-relax the variable, if necessary
5. Repeat steps 1 through 4 until convergence

ADVANTAGES:

Simple to program; takes less computer memory

DISADVANTAGES:

It is difficult to make a decision in which order the equations must be solved to ensure convergence

SOLUTION PROCEDURE

NEWTON-RAPHSON METHOD

STEPS:

1. Guess a solution for each variable in the system of equations
2. Calculate the residuals of each equation
3. Develop a set of correction equations for all variables
4. Solve for the correction equations by Gaussian Elimination method
5. Apply correction to each variable
6. Iterate until the corrections become very small

ADVANTAGES:

No decision making process is involved to determine the order in which equations must be solved

DISADVANTAGES:

Requires more computer memory; difficult to program.

SOLUTION PROCEDURE

SASS (Simultaneous Adjustment with Successive Substitution) Scheme

- **SASS is a combination of successive substitution and Newton-Raphson method**
- **Mass conservation and flowrate equations are solved by Newton-Raphson method**
- **Energy Conservation and concentration equations are solved by successive substitution method**
- **Underlying principle for making such division:**
  - **Equations which have strong influences to other equations are solved by the Newton-Raphson method**
  - **Equations which have less influence to other are solved by the successive substitution method**
- **This practice reduces code overhead while maintains superior convergence characteristics**

GFSSP Solution Scheme

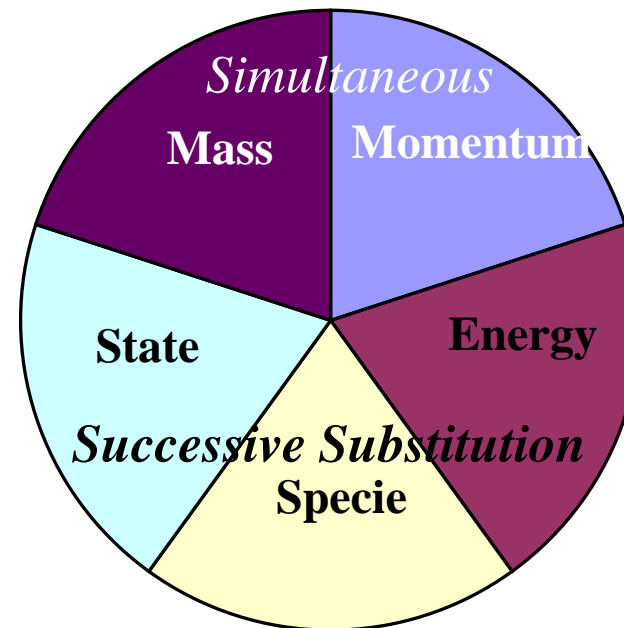**SASS** : **S**imultaneous **A**djustment
with **S**uccessive **S**ubstitution

Approach : Solve simultaneously
when equations are strongly
coupled and non-linear

Advantage : Superior
convergence characteristics with
affordable computer memory

CONVERGENCE

- Numerical solution can only be trusted when fully converged
- GFSSP's convergence criterion is based on difference in variable values between successive iterations. Normalized Residual Error is also monitored
- GFSSP's solution scheme has two options to control the iteration process
  - Simultaneous (SIMUL = TRUE)
  - Non-Simultaneous (SIMUL = FALSE)

CONVERGENCE

Simultaneous Option

- ## Single Iteration Loop

  - First solve mass, momentum and equation of state by the Newton-Raphson (NR) scheme

  - Next solve energy and specie conservation equation by Successive Substitution (SS) scheme

  - Solution is converged when the normalized maximum correction, Δ_{max} is less than the convergence criterion

$$\Delta_{max} = MAX \left| \sum_{i=1}^{N_E} \frac{\Phi_i'}{\Phi_i} \right|$$ N_E is the total number of equations solved by the Newton-Raphson scheme
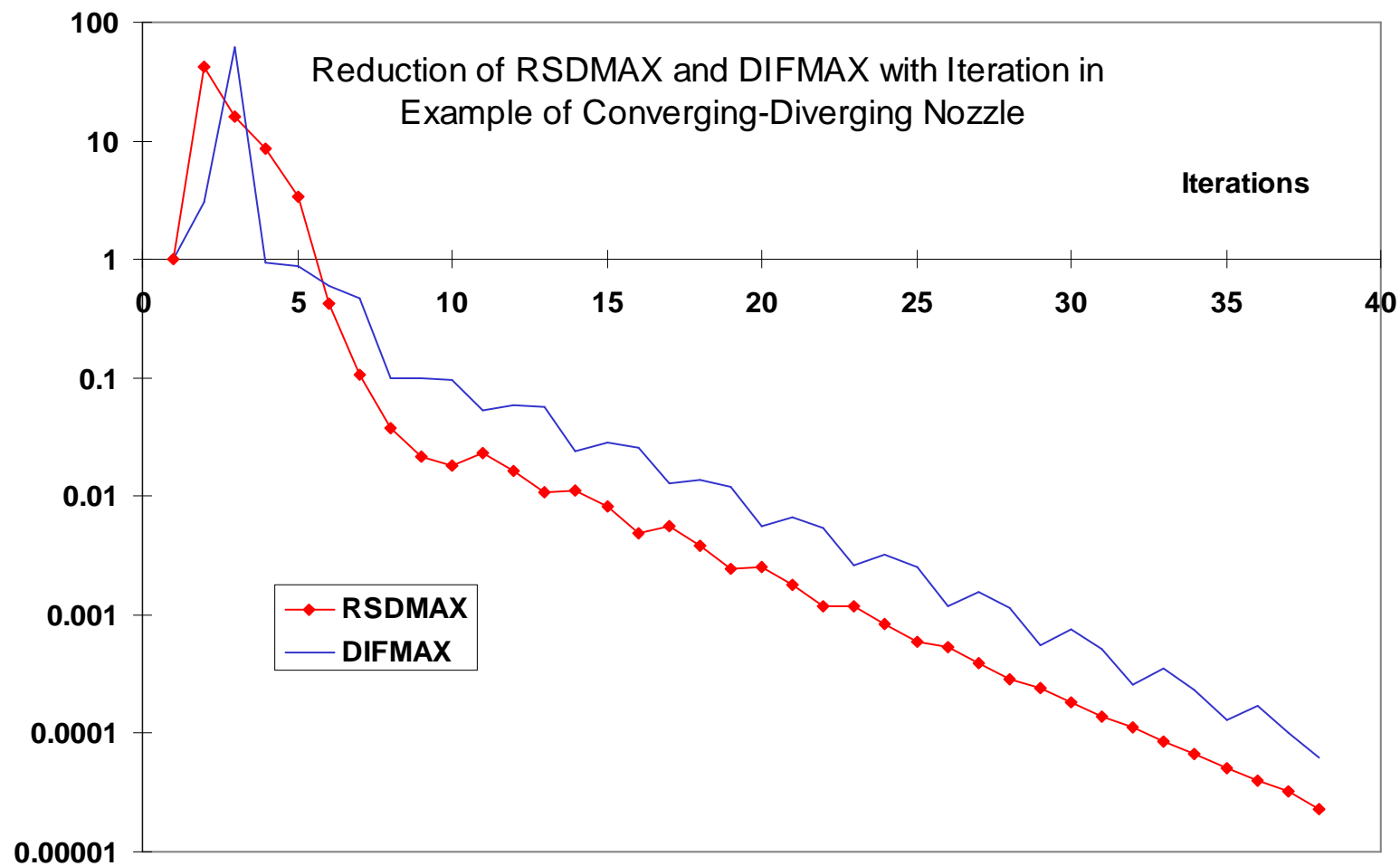
CONVERGENCE

Non-Simultaneous Option

- Inner & Outer Iteration Loop

  – Mass, Momentum and Equation of state is solved in inner iteration loop by NR scheme

  – Energy and Specie conservation equations are solved in outer iteration loop by SS scheme

  – Convergence of NR scheme is determined by Δ^i_{max}

  – Convergence of SS scheme is determined by Δ^o_{max}

$$\Delta^o_{max} = MAX\left|\Delta_{K_f}, \Delta_\rho, \Delta_h \text{ or } \Delta_s\right| \qquad \Delta_{K_f} = MAX\left|\sum_{i=1}^{N_B} \frac{K'_f}{K_f}\right| \qquad \text{etc.}$$
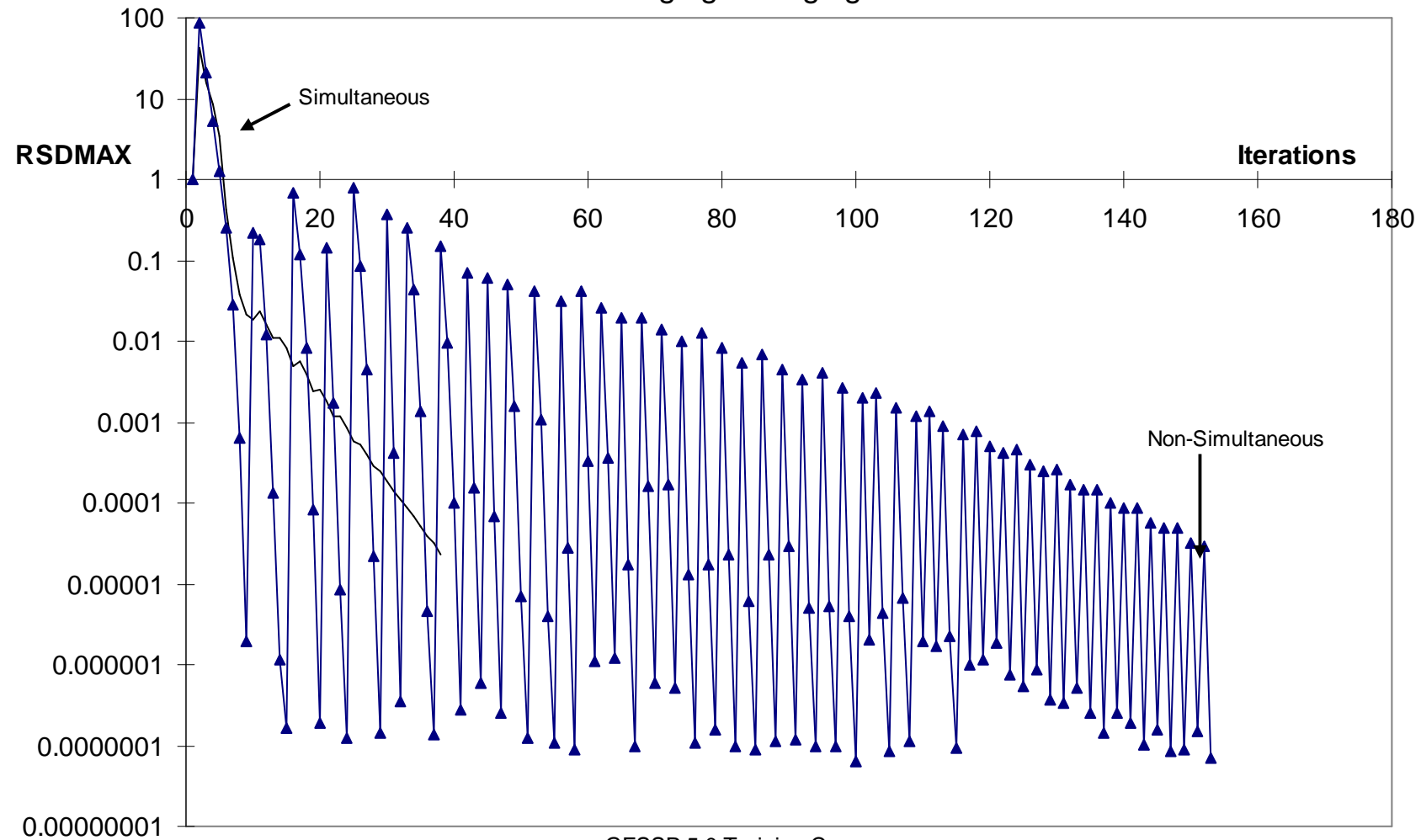
Comparison of Convergence Characteristics between Simultaneous and Non-Simultaneous Option in Converging-Diverging Nozzle

SOLUTION PROCEDURE
Summary

- Simultaneous option is more efficient than Non-Simultaneous option

- Non-Simultaneous option is recommended when Simultaneous option experiences numerical instability

- Under-relaxation and good initial guess also help to overcome convergence problem

- A lack of realism in problem specification can lead to convergence problem

- Lack of realism includes:
  - Unrealistic geometry and/or boundary conditions
  - Attempt to calculate properties beyond operating range

Conjugate Heat Transfer

Legend:

- ▣ Boundary Node
- ☐ Internal Node
- ──⬭▶ Branches

- ▪ Solid Node
- ◯ Ambient Node
- ⟷ Conductor
  - ◀▬▶ Solid to Solid
  - ◀┈┈▶ Solid to Fluid
  - <-–> Solid to Ambient
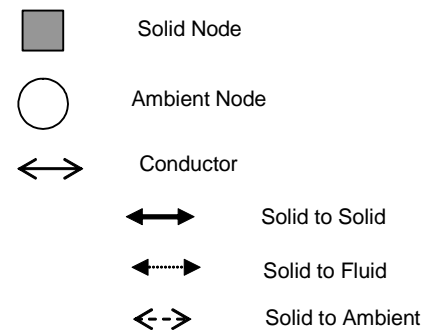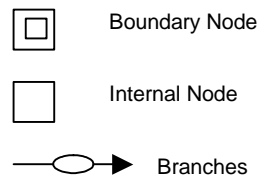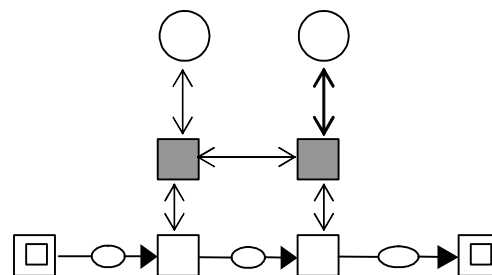
Mathematical Closure

Unknown Variables

1. Pressure

2. Flowrate

3. Fluid Temperature

4. Solid Temperature

5. Specie Concentrations

6. Mass

Available Equations to Solve

1. Mass Conservation Equation

2. Momentum Conservation Equation

3. Energy Conservation Equation of Fluid

4. Energy Conservation Equation of Solid

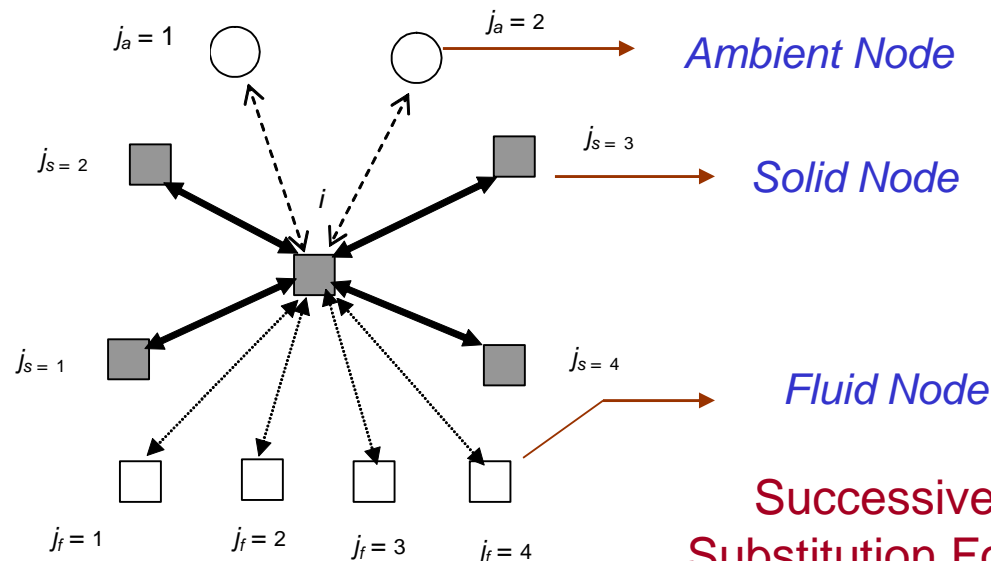5. Conservation Equations for Mass Fraction of Species

6. Thermodynamic Equation of State

Heat Conduction Equation

$j_a = 1$ $j_a = 2$ *Ambient Node*

$j_{s=2}$ $j_{s=3}$ *Solid Node*

i

$j_{s=1}$ $j_{s=4}$ *Fluid Node*

$j_f = 1$ $j_f = 2$ $j_f = 3$ $j_f = 4$

Conservation Equation

Successive Substitution Form

$$\frac{\partial}{\partial \tau}\left(mC_p T_s^i\right) = \sum_{j_s=1}^{n_{ss}} \dot{q}_{ss} + \sum_{j_f=1}^{n_{sf}} \dot{q}_{sf} + \sum_{j_a=1}^{n_{sa}} \dot{q}_{sa} + \dot{S}_i$$

$$\dot{q}_{ss} = k_{ij_s} A_{ij_s} / \delta_{ij_s} \left(T_s^{j_s} - T_s^i\right)$$

$$\dot{q}_{sf} = h_{ij_f} A_{ij_f} \left(T_f^{j_f} - T_s^i\right)$$

$$\dot{q}_{sa} = h_{ij_a} A_{ij_a} \left(T_a^{j_a} - T_s^i\right)$$

$$T_s^i = \frac{\displaystyle\sum_{j_s=1}^{n_{ss}} C_{ij_s} T_s^{j_s} + \sum_{j_f=1}^{n_{sf}} C_{ij_f} T_f^{j_f} + \sum_{j_a=1}^{n_{sa}} C_{ij_a} T_a^{j_a} + \frac{(mC_p)_m}{\Delta \tau} T_{s,m}^i + \dot{S}}{\displaystyle\frac{mC_p}{\Delta \tau} + \sum_{j_s=1}^{n_{ss}} C_{ij_s} + \sum_{j_f=1}^{n_{sf}} C_{ij_f} + \sum_{j_a=1}^{n_{sa}} C_{ij_a}}$$

SASS Solution Scheme
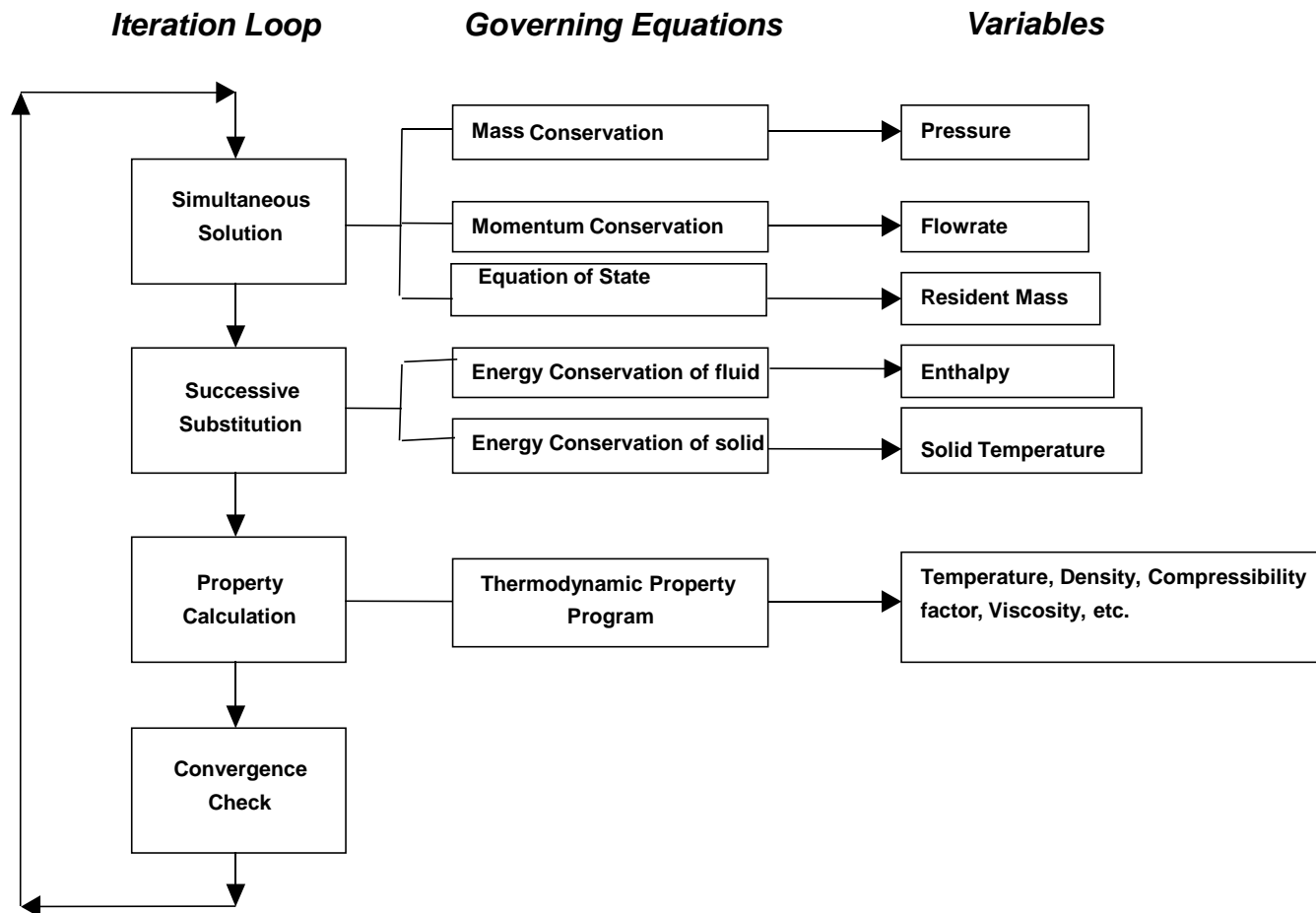
Iteration Loop	Governing Equations	Variables

Simultaneous Solution
- Mass Conservation → Pressure
- Momentum Conservation → Flowrate
- Equation of State → Resident Mass

Successive Substitution
- Energy Conservation of fluid → Enthalpy
- Energy Conservation of solid → Solid Temperature

Property Calculation
- Thermodynamic Property Program → Temperature, Density, Compressibility factor, Viscosity, etc.

Convergence Check
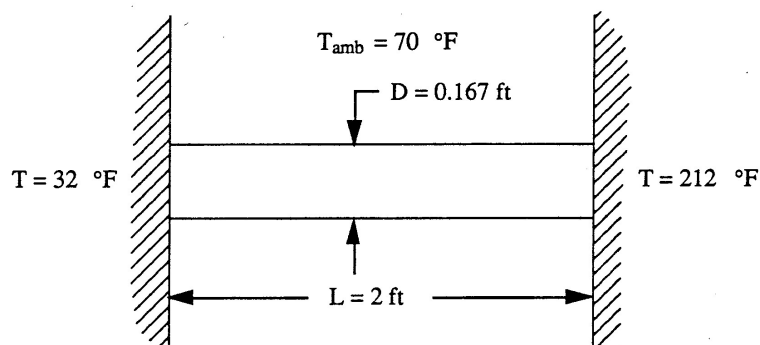
Problem Considered
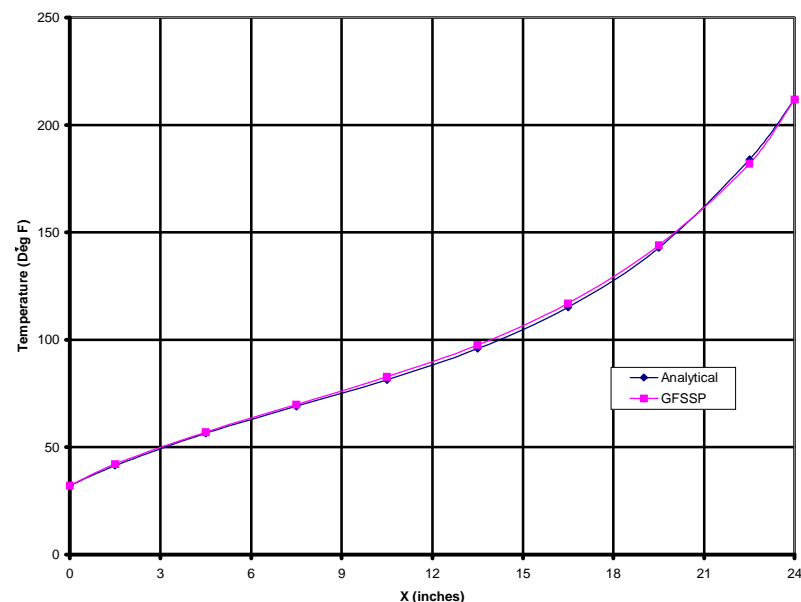
Comparison with Analytical Solution

GFSSP Model

Advanced Applications

- ## Modeling Cryogenic Transfer Line

  - ### Validation of CHT Capability

- ## Modeling of Propellant Loading

  - ### Model Verification by comparing with Space Shuttle Data

Saturated LH$_2$ chilldown time for various driving pressures

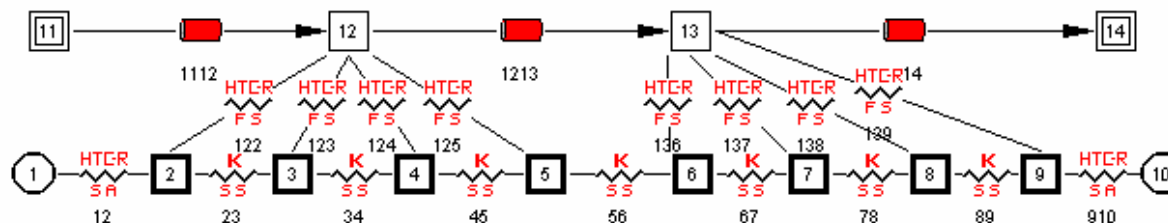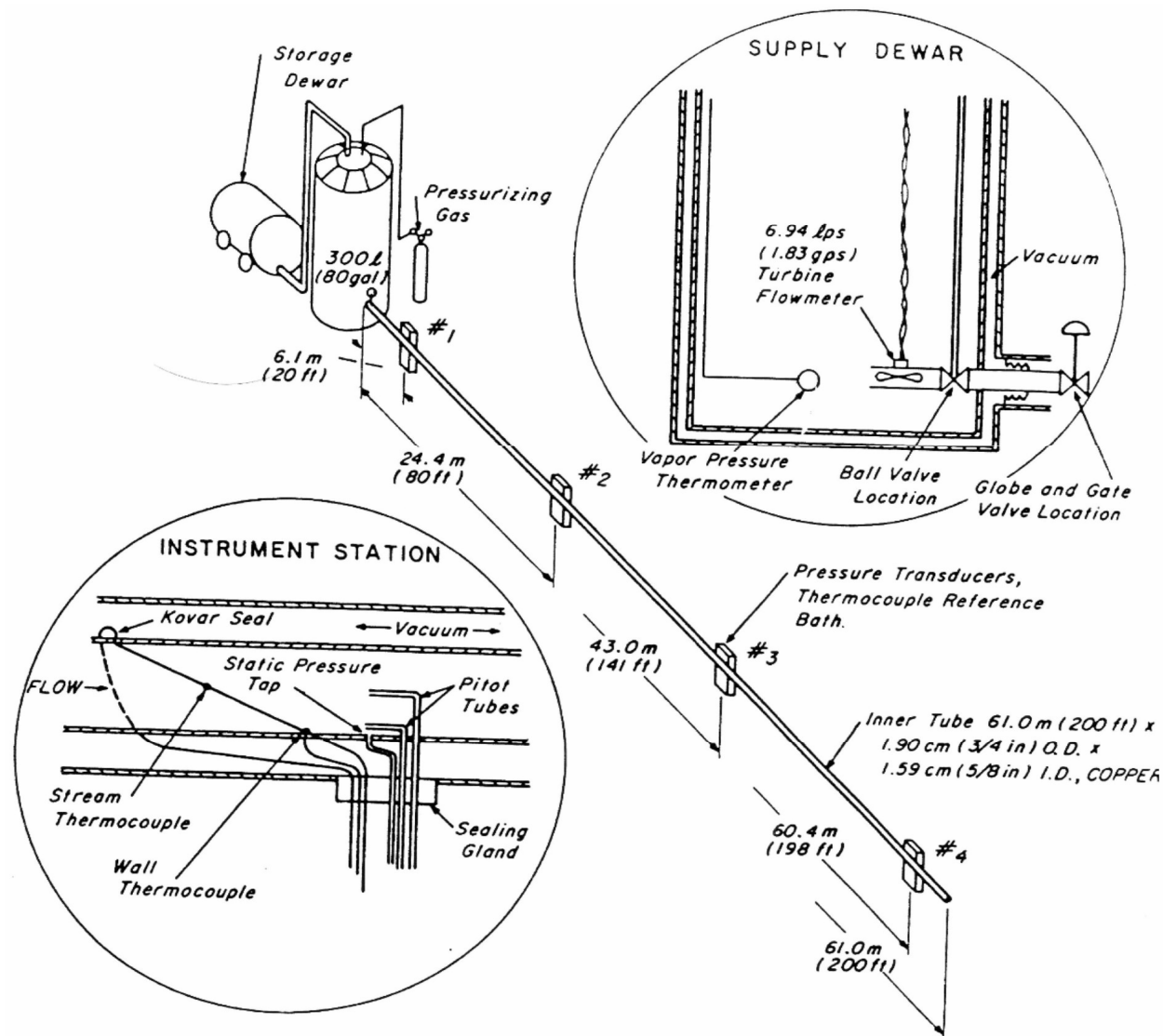| Driving Pressure (psia)	Saturation Temperature (°F)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
74.97	−411.06	68	70
86.73	−409.08	62	69
111.72	−406.4	42	50
161.72	−402.13	30	33

Subcooled LH$_2$ chilldown time for various driving pressures. LH$_2$ is subcooled at –424.57 ºF

Driving Pressure (psia)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
36.75	145	150
61.74	75	80
86.73	62	60
111.72	41	45
136.72	32	38
161.7	29	30

Saturated LN$_2$ chilldown time for various driving pressures

Driving Pressure (psia)	Saturation Temperature (°F)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
61.74	−294.09	155	185
74.97	−289.71	150	160
86.73	−286.24	130	140

Subcooled LN$_2$ chilldown time for various driving pressures. LN$_2$ is subcooled at –322.87 ºF

Driving Pressure (psia)	Experimental Chilldown Time (s)	Predicted Chilldown Time (s)
36.75	222	250
49.97	170	175
61.74	129	140
74.97	100	100
86.73	95	90

Comparison of temperature histories for subcooled LH$_2$ for various driving pressures

Station #1 (violet) —20 ft from tank inlet

Station #2 (red) —80 ft from tank inlet

Station #3 (green) —141 ft from tank inlet

Station #4 (blue) —198 ft from tank inlet

p=36.74 psia

p=61.72 psia
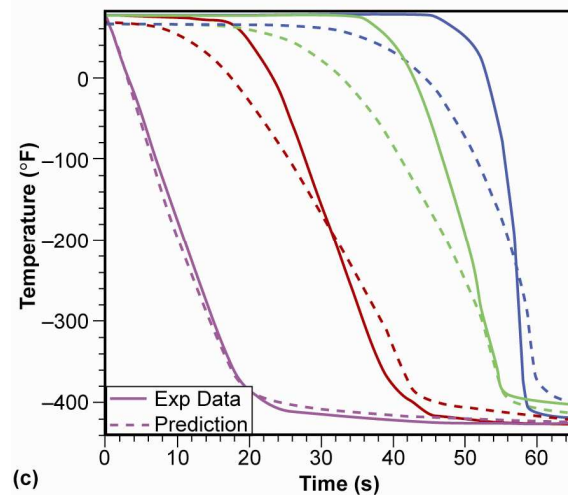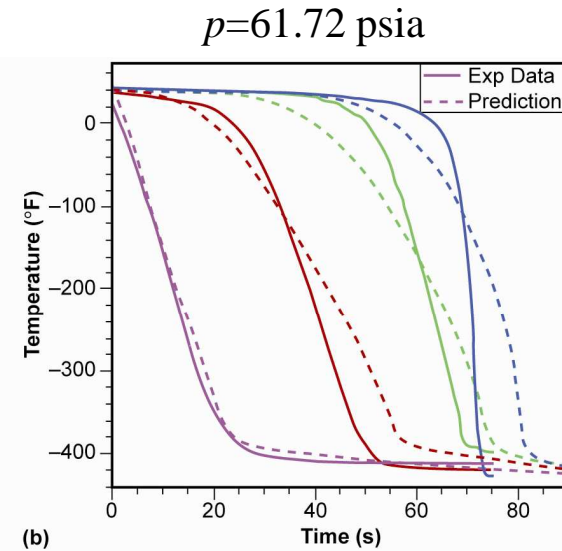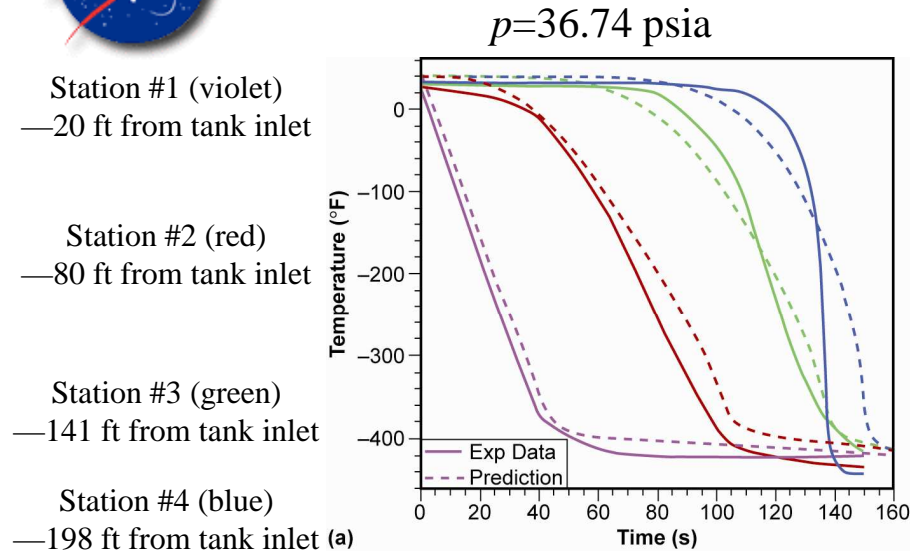
p=86.7 psia
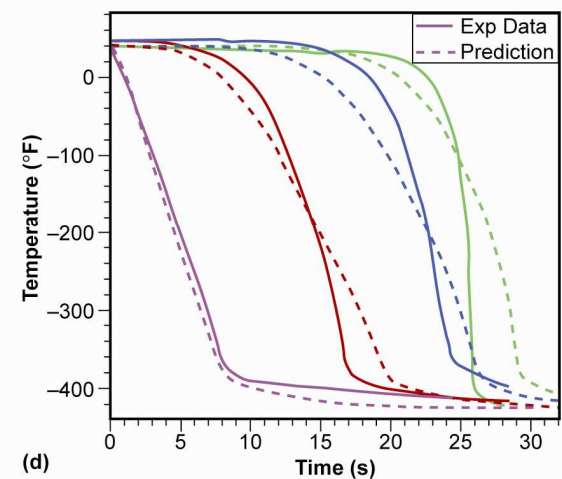
p=161 psia

Propellant Loading in Launch Complex 39B
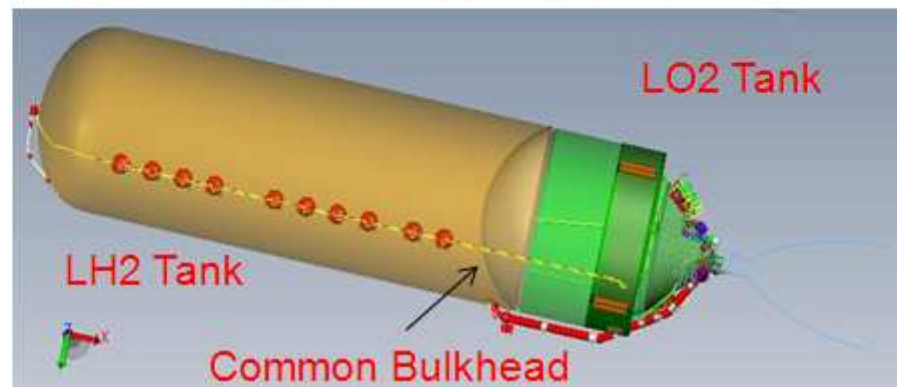
Requirements for Propellant Loading

- **LH2 Loading**
  - Slow fill – 2 lb/sec until Tank is 5% full
  - Fast fill – 15 lb/sec until Tank is 95% full
  - Topping – 2 lb/sec until Tank is 100% full
  - Replenish – 1 lb/sec to allow replenishment due to boil-off

- **LO2 Loading**
  - Slow fill – 9 lb/sec until Tank is 5% full
  - Fast fill – 93 lb/sec until Tank is 95% full
  - Topping – 9 lb/sec until Tank is 100% full
  - Replenish – 1 lb/sec to allow replenishment due to boil-off

- **Pre-chill**
  - Chilling of both tanks should start simultaneously to maintain a favorable thermal gradient across Common Bulkhead
  - LH2 loading can only start after completion of LO2 loading followed by 15 minutes of pressure test
  - Tank pressure must not exceed 10 psig during loading

GFSSP Model of LH2 Tank Loading of Ares I Upper Stage
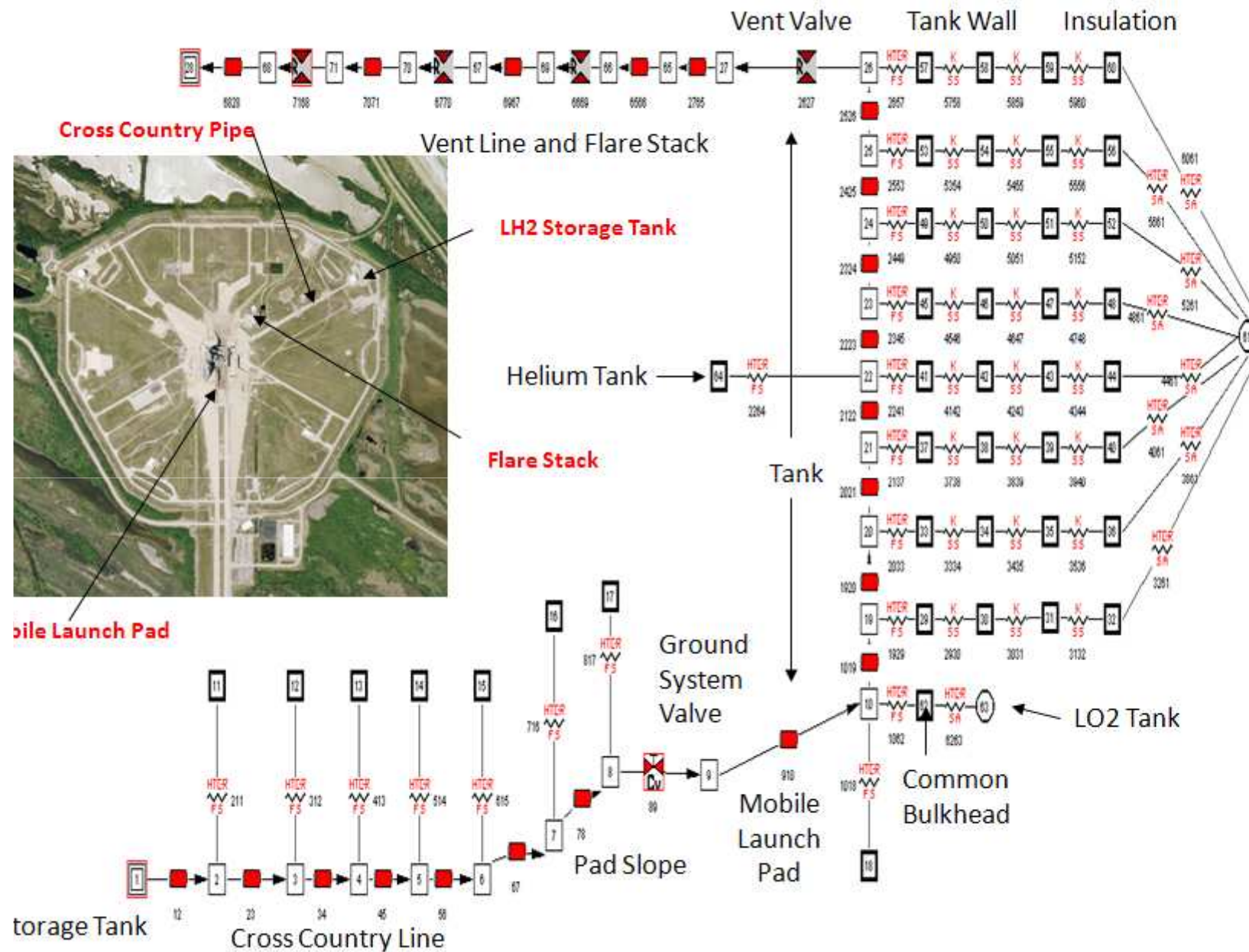
Input Data for Integrated Ground System, LH$_2$ Tank and Flare Stack Model of Propellant Loading
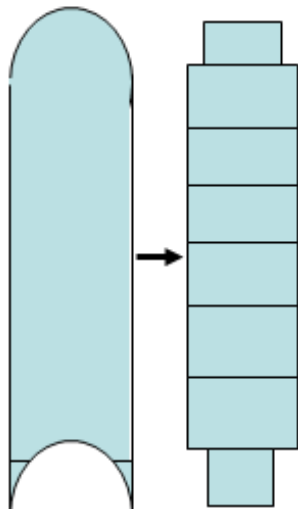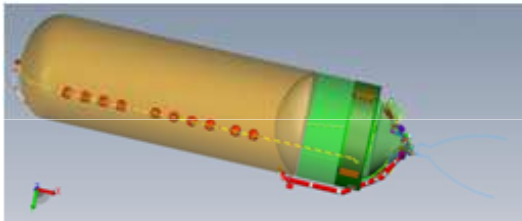
LH2 Storage Tank Pressure	46.3 psia
Ambient Temperature	85 ° F
LH2 Propellant Load	48593 lb
Pre-Chill Valve C_v	16
Slow Fill & Topping Valve C_v	12
Fast Fill Valve C_v	140
Replenish Valve C_v	5.64
Vent Valve Area	20.94 in^2
Vent Valve C_d	0.552
Ground System Pipe Length and Volume	1910 ft / 879 ft^3
Flare Stack Pipe Length and Volume	1305 ft /1605 ft^3
Tank Volume	11,620 ft^3
Ground System Pipe Mass	29314 lb
Tank Mass	8742 lb
Foam Mass	673 lb
Metal (Al-Li) thickness	0.1934 in
Foam (BX-265) thickness (Tank Barrel)	1 in
Foam (BX-265) thickness (Dome)	0.5 in
Common Bulkhead Conductance	0.045 Btu/hr-ft^2-F

Summary Result for LH2 Loading

Pre-chill Time (after start)	129 Minutes
5% Tank Fill Time (after pre-chill)	23 Minutes
95% Tank Fill Time (after pre-chill)	73 Minutes
100% Tank Fill Time (after pre-chill)	87 Minutes
Tank Chill-down Time (after start)	194 Minutes
Maximum Tank Pressure (pre-chill)	15.94 psia
Maximum Ullage Pressure (Replenish)	14.89 psia
Maximum Vent Flowrate	0.94 lb/sec
Amount of GH2 Vented	3993lb
Minimum Foam Surface Temperature	6.2 F

Tank Inflow rate and Vent flow rate
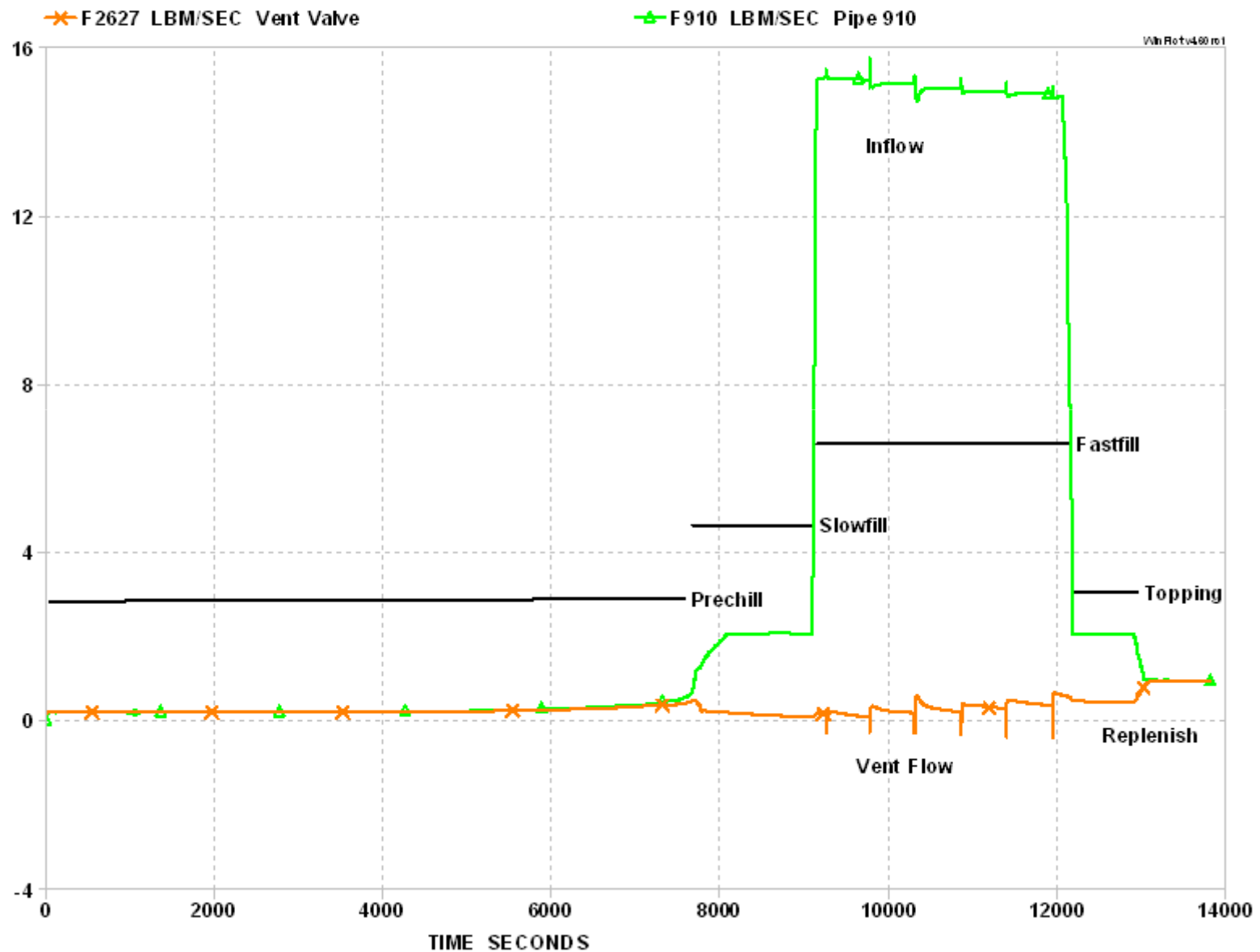
Propellant Temperature and Quality in LH2 Tank
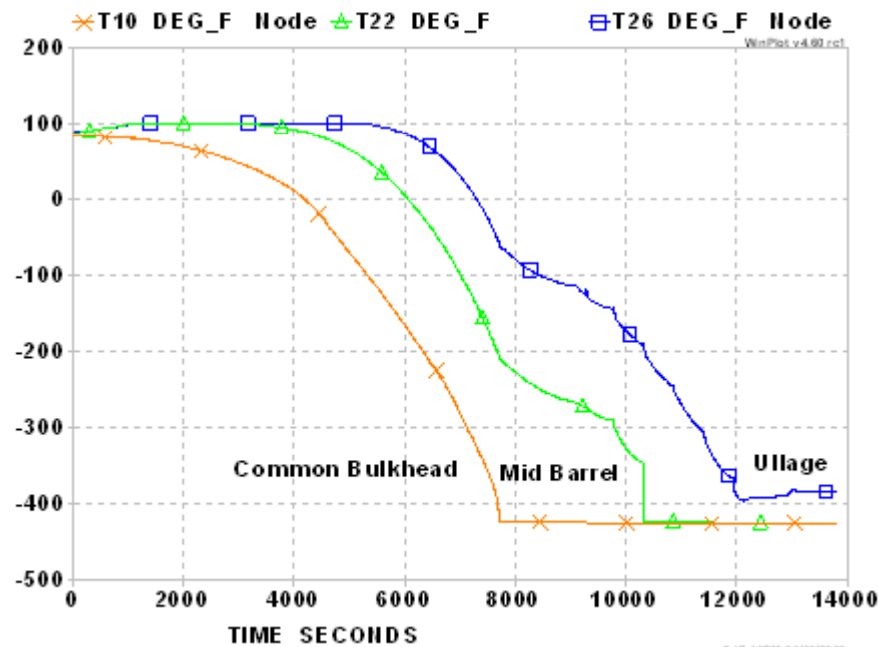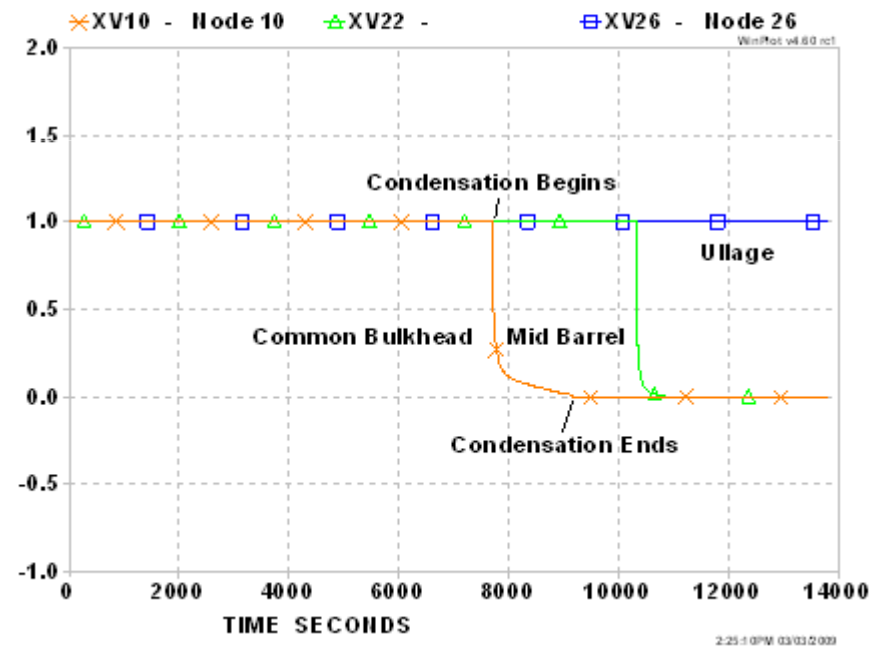
Shuttle ET LH$_2$ Propellant Loading
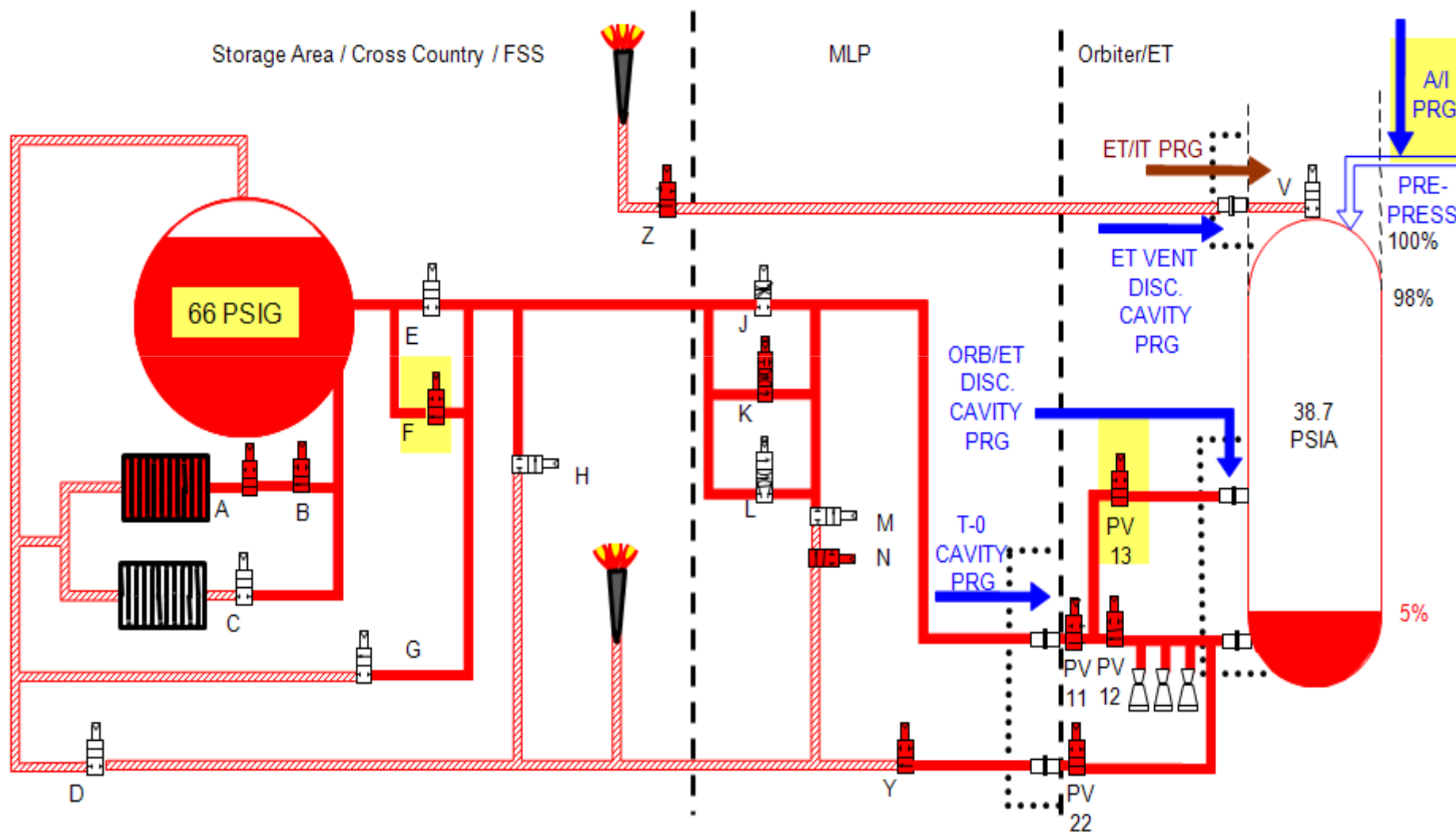
Shuttle ET LH$_2$ Propellant Loading

Loading Phase	Start Time (Approx.)	Flowrate (lb$_m$/s)
Transfer Line Chill	T-7h55m	≈1
Pressurize Storage Tank and ET	T-7h51m	10
Slow Fill to 5%	T-7h42m	10
Fast Fill to 72%	T-7h5m	73
Fast Fill to 85%	T-6h39m	52
Reduced Fast Fill to 98%	T-6h18m	10
Topping and Replenish (not modeled)	T-5h54m	≈1

KSC LH$_2$ Facility Properties

- **Cross-country pipeline**
  - ¼ mile of 10" Invar pipe, vacuum-jacketed
  - 26,400 lb$_m$
  - $\Delta z = 79'$

- **Mobile launch platform**
  - 334' of 8" and 10" stainless steel pipe, vacuum-jacketed
  - 6100 lb$_m$
  - $\Delta z = 43'$

ET LH$_2$ Tank Properties

- **Tank mass: 23,600 lb$_m$**

- **LH$_2$ mass: 227,600 lb$_m$**

- **Length: 97 ft**

- **Diam: 27.6 ft**

- **Insulation: 2078 lb$_m$**
  - ≈ 1.0 in NCFI on barrel and aft dome
  - ≈ 0.75 in BX-265 on forward dome

- **Surface area: 8550 ft^2**

- **Vent: C$_d$A = f(ΔP) ≈ 18 in^2**
  - Open during facility line chilldown
  - Cycles open and closed during slow/fast fill to maintain 24-27 psig

ET LH$_2$ GFSSP Model
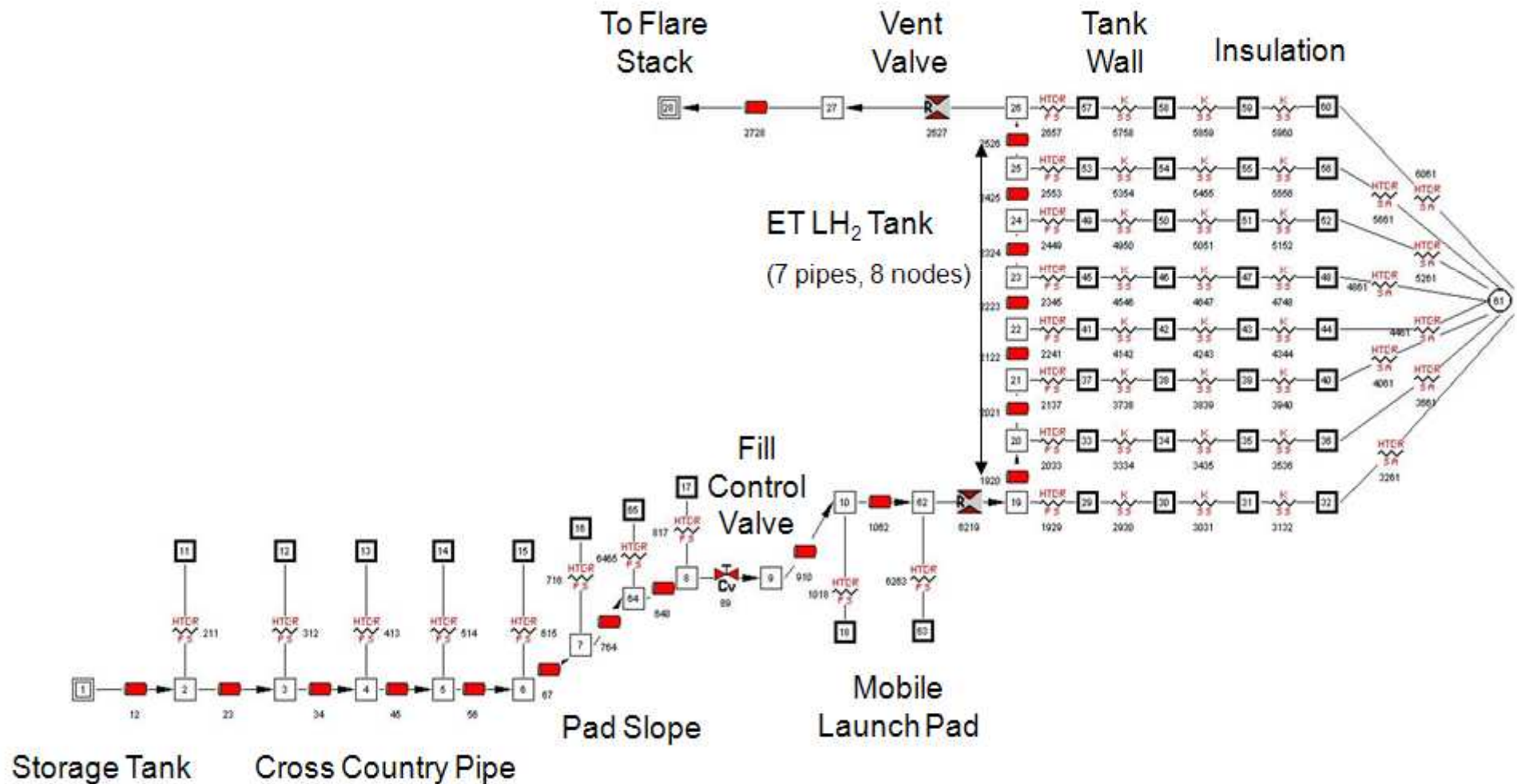
Comparison

	STS-116	GFSSP
5% Full	48 min (T-7h7m)	50 min (T-7h5m)
98% Full	119 min (T-5h56m)	116 min (T-5h59m)
Tank chilled (to -420 F)	N/A	106 min (T-6h9m)
H_2 Vented During Loading	N/A	4931 lb_m
Heat Leak (through tank walls)	* 68 - 140 BTU/s	96 BTU/s

* Not measured. Estimate from ET System Definition Handbook.

Pressure at Valve Skid
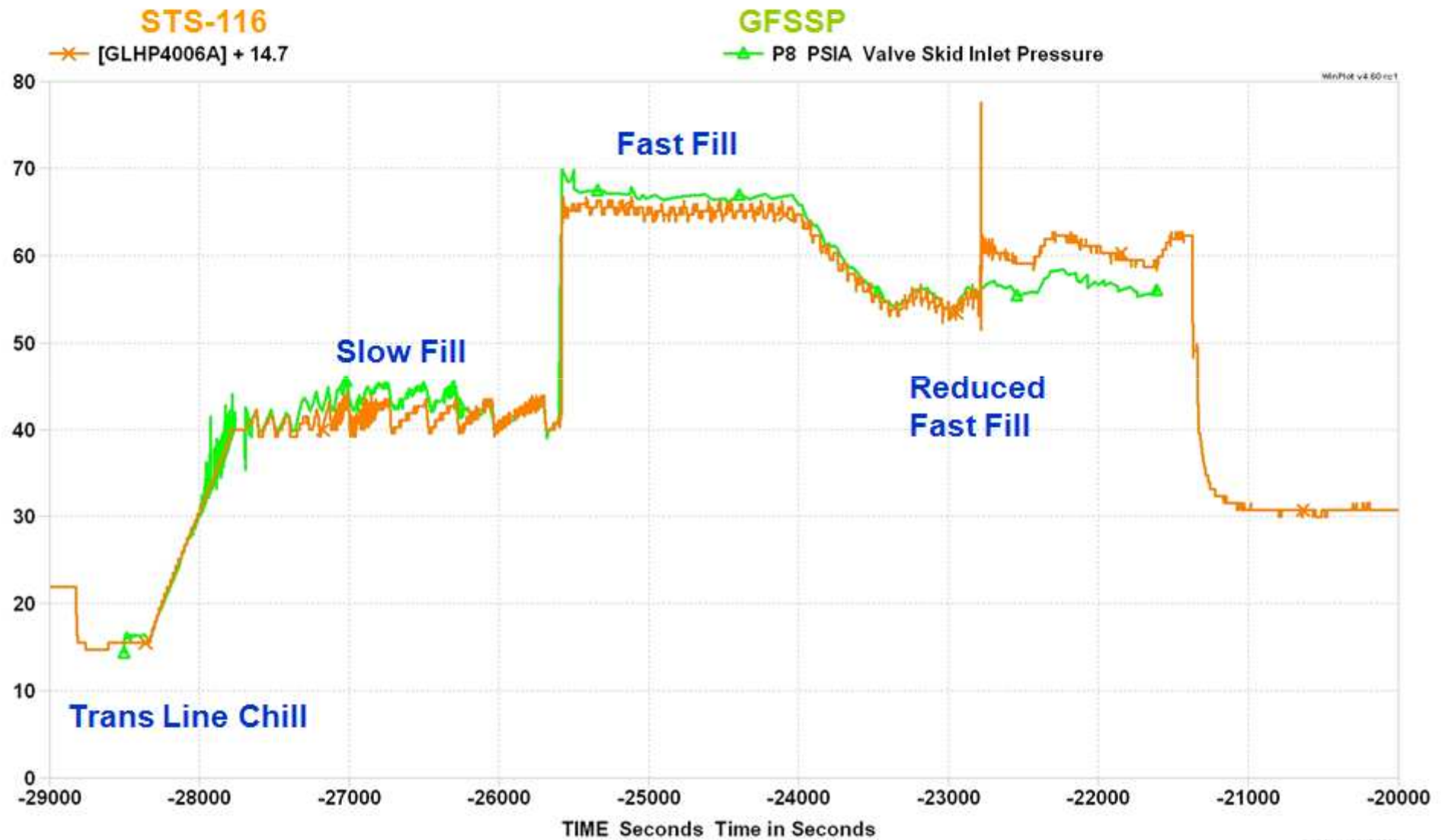
Summary

- **GFSSP has been extended to model conjugate heat transfer**
- **Fluid Solid Network Elements include**:
    - Fluid nodes and Flow Branches
    - Solid Nodes and Ambient Nodes
    - Conductors connecting Fluid-Solid, Solid-Solid and Solid-Ambient Nodes
- **Heat Conduction Equations are solved simultaneously with Fluid Conservation Equations for Mass, Momentum, Energy and Equation of State**
- **The extended code was verified by comparing with analytical solution for simple conduction-convection problem**
- **The code was applied to model**
    - Pressurization of Cryogenic Tank
    - Freezing and Thawing of Metal
    - Chilldown of Cryogenic Transfer Line
    - Boil-off from Cryogenic Tank

USER SUBROUTINE

Solver Module/function   **User Subroutine/**function

MAIN		FILENUM
Controls program	← →	Defines input and output files numbers within the code

		TSTEP
	← →	Allows user to overwrite the input deck defined time step

READIN		USRSET
Reads input data file	← →	Allows user to redefine input file to custom format

INIT		USRINT
Provides initial value and steady state boundary conditions	← →	Allows user to overwrite initial values and steady state boundary conditions

BOUND		BNDUSER
Provides time-dependant boundary conditions from history file	← →	Allows user to define time-dependant boundary conditions

EQNS		SORCEM
Generates mass & momentum conservation equations along with equation of resident mass	← →	Allows user to provide an external mass source
	← →	**SORCEF** Allows user to provide an external momentum source

Contents

- Motivation & Benefit

- Program Structure

- Solution Algorithm

- Solver-User Subroutine Interaction

- Data Structure

- Indexing Subroutines

- Example & Demonstration

MOTIVATION AND BENEFIT

- <u>Motivation</u>: To allow users to access GFSSP solver module to develop additional modeling capability

- <u>Benefit</u>: GFSSP users can work independently without Developer's active involvement

How do they work?

- A series of subroutines are called from various locations of solver module

- The subroutines do not have any code but includes the common block

- The users can write FORTRAN code to develop any new physical model in any particular node or branch

What users need to do?

– Users need to compile a new file containing all user routines and link that with GFSSP to create a new executable

GFSSP – Program Structure

Solver & Property Module

Graphical User Interface (VTASC)

User Subroutines

- Equation Generator
- Equation Solver
- Fluid Property Program

New Physics

Input Data File

- Time dependent process
- non-linear boundary conditions
- External source term
- Customized output
- New resistance / fluid option

- Creates Flow Circuit
- Runs GFSSP
- Displays results graphically

Output Data File

Flow chart of Solution Algorithm

Marshall Space Flight Center

Start

READIN - Reads input data from data file generated by VTASC

Obtain a trial solution

INIT – Generate Trial Solution

GASP & Wasp or GASPAK – A routine for thermodynamic properties

Iteration loop repeated for each time step

BOUND – Supply Time-dependant boundary conditions

COEF – Constructs the coefficient matrix of the correction equation

EQNS – Calculates residuals of three governing equations

Mass conservation

Momentum Conservation

Simultaneous (S) solution of pressure, flowrate, and resident maas

NEWTON – Controls the iteration loop of Newton-Raphson scheme

SOLVE – Solve correction equation by Gaussian elimination method

Equation of State

Successive Substitution (SS) solution of enthalpy & concentration

ENTHALPY – Solves enthalpy by SS method

UPDATE – After applying corrections update each variable (11)

MASSC – Solves concentration by SS method

Energy Conservation

Specie Conservation

Solution of Temperature of Solid

TSOLID or TSOLIDNR – Solves temperature by SS or S method

Solid Temperature

Calculate flow resistances

RESIST – Calculates resistances for all branches

DENSITY – Calculates density and other properties

GASP & Wasp or GASPAK – A routine for thermodynamic properties

KFACT1 – KFACT21 Calculates branch resistances

Convergence check

Description of User Subroutines

Fifteen User Subroutines were provided:

- SORCEM: External Mass Source

- SORCEF: External Force

- SORCEQ: External Heat source

- SORCEC: External Concentration source

- KFUSER: New resistance option

- PRPUSER: New fluid property

- TSTEP: Variable time step during a transient run
- BNDUSER: Variable boundary condition during
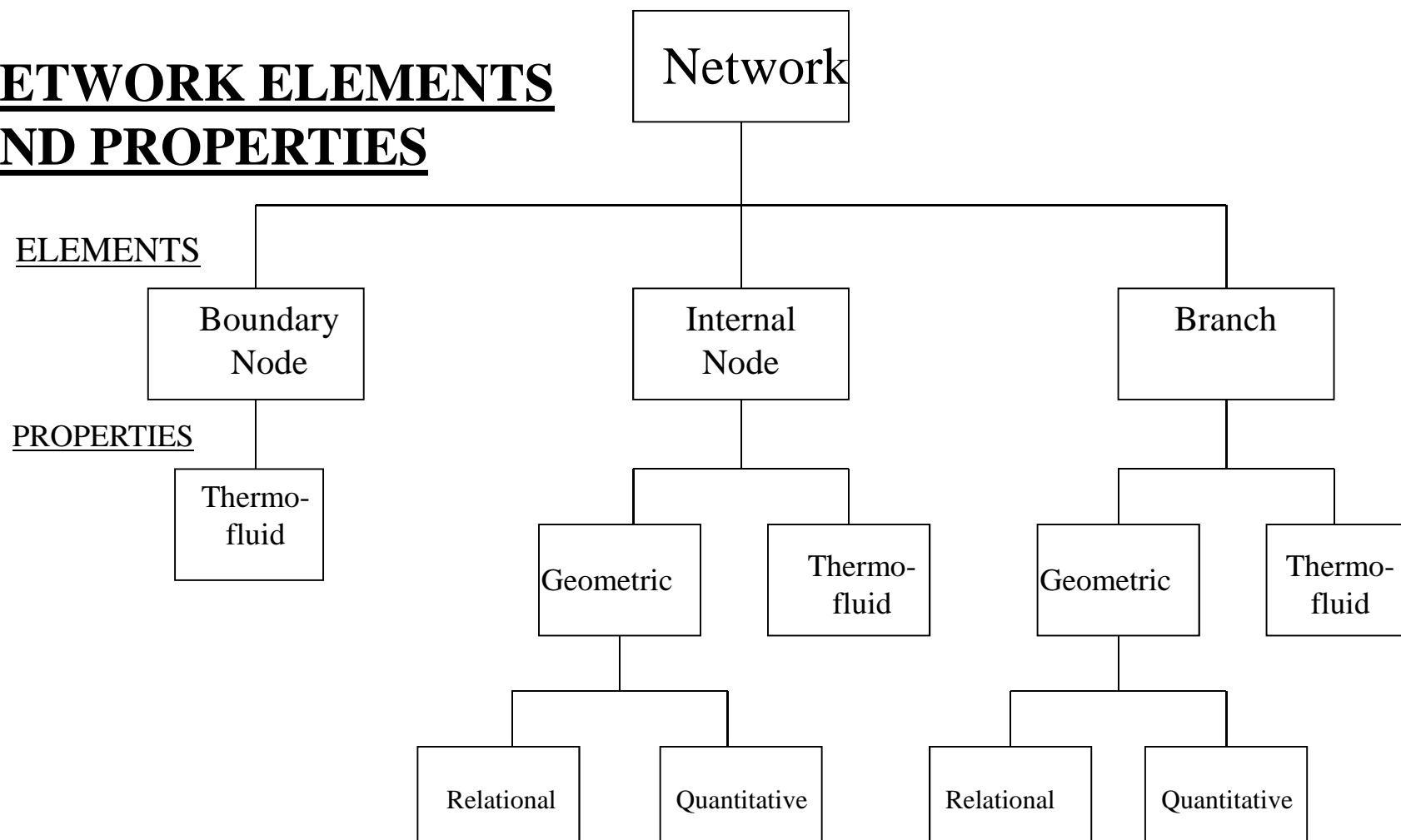 transient   run

Description of User Subroutines

– USRINT: Provide initial values and steady state boundary conditions

– PRNUSER: Additional print out or creation of additional file for post processing

– FILNUM: Assign file numbers; users can define new file numbers

– USRSET: User can supply all the necessary information by writing their own code

– SORCETS: External Heat Source in Solid Node

– USRHCF: New Heat Transfer Correlation

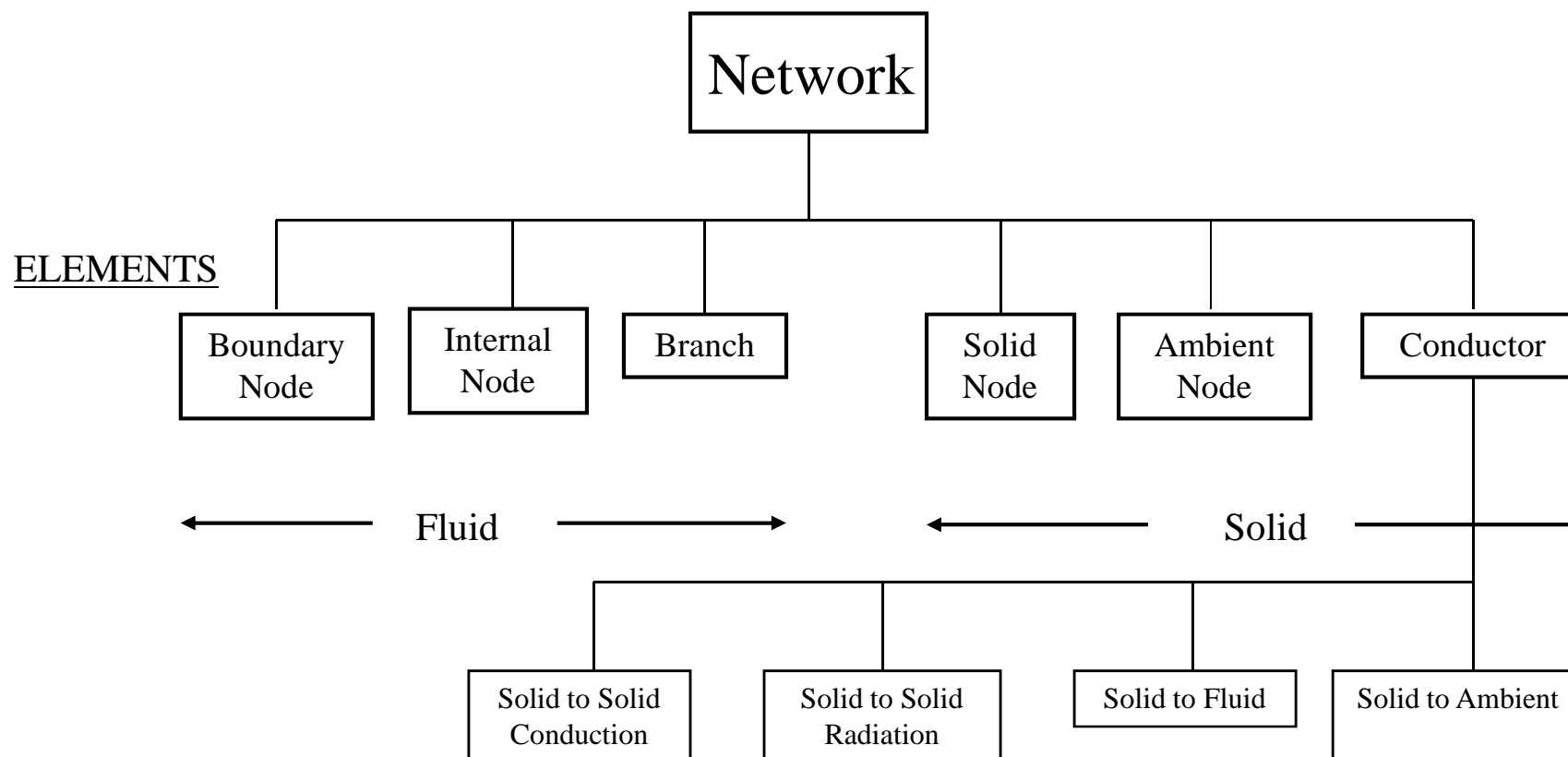– USRADJUST: Solution adjustment to satisfy design requirement

DATA STRUCTURE FOR FLOW ANALYSIS

NETWORK ELEMENTS AND PROPERTIES
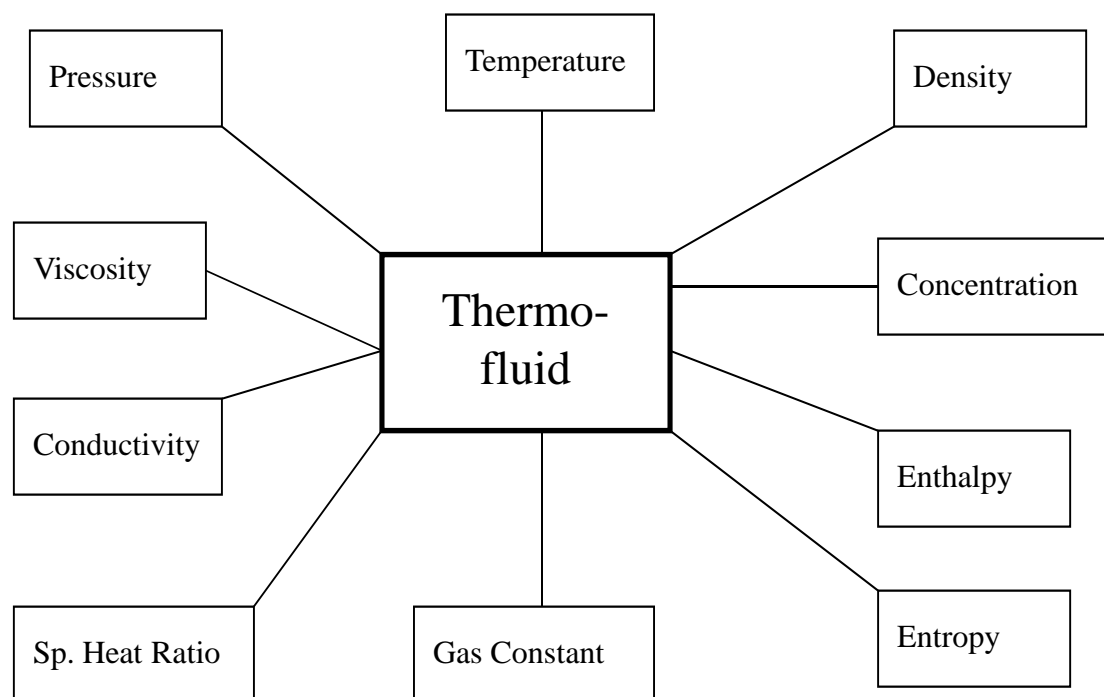
ELEMENTS

PROPERTIES

Network

Boundary Node

Internal Node

Branch

Thermo-fluid

Geometric

Thermo-fluid

Geometric

Thermo-fluid

Relational

Quantitative

Relational

Quantitative

Extended Data Structure for Conjugate Heat Transfer

INTERNAL & BOUNDARY NODE THERMOFLUID PROPERTIES

INTERNAL NODE GEOMETRIC PROPERTIES

```
                          ┌─────────────┐
                          │  Geometric  │
                          └──────┬──────┘
              ┌──────────────────┴──────────────────┐
        ┌───────────┐                          ┌──────────────┐
        │ Relational│                          │ Quantitative │
        └─────┬─────┘                          └──────┬───────┘
      ┌───────┴────────┐                              │
 ┌──────────┐   ┌───────────────────────┐      ┌──────────┐
 │          │   │   NAMEBR(I, 1)         │      │  VOLUME  │
 │ NUMBR(I )│   ├───────────────────────┤      └──────────┘
 │          │   │   NAMEBR(I, 2)         │
 └──────────┘   ├───────────────────────┤
                │   . . . . . . . . . .  │
                ├───────────────────────┤
                │  NAMEBR(I, NUMBR(I))   │
                └───────────────────────┘
```
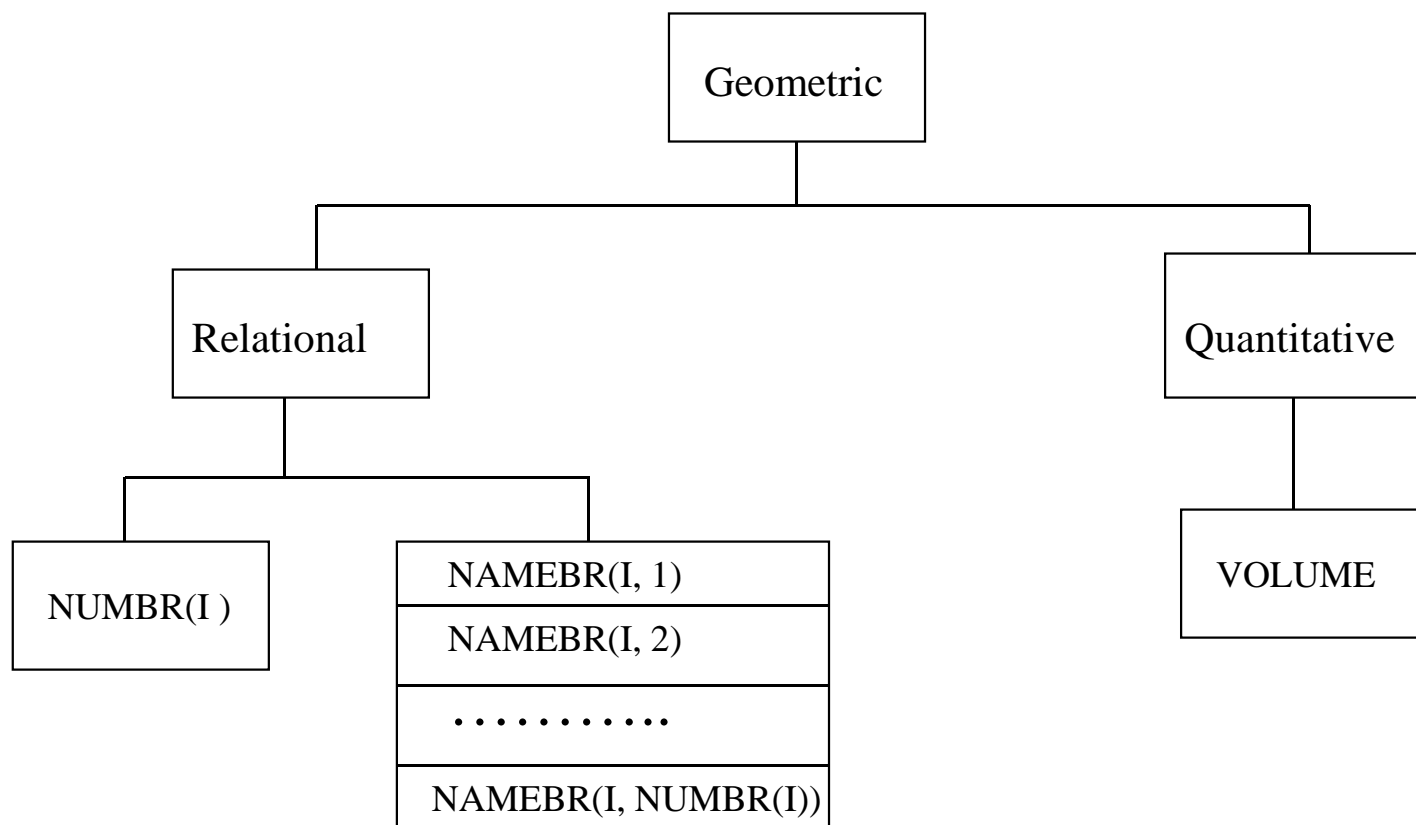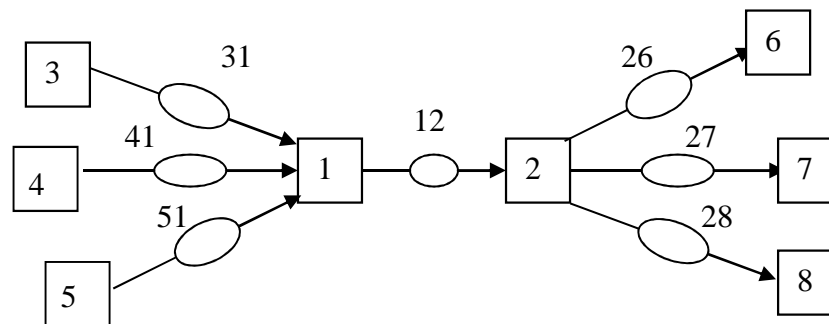
NUMBR – Number of branches
connected to the node

NAMEBR – Name of the branches connected to
the node

EXAMPLE OF NODE RELATIONAL PROPERTY

Relational Property of Node 1

Number of branches connected to Node I, NUMBR(I) = 4

Name of the Branches connected to Node I,

NAMEBR(I,1) = 31

NAMEBR(I,2) = 41
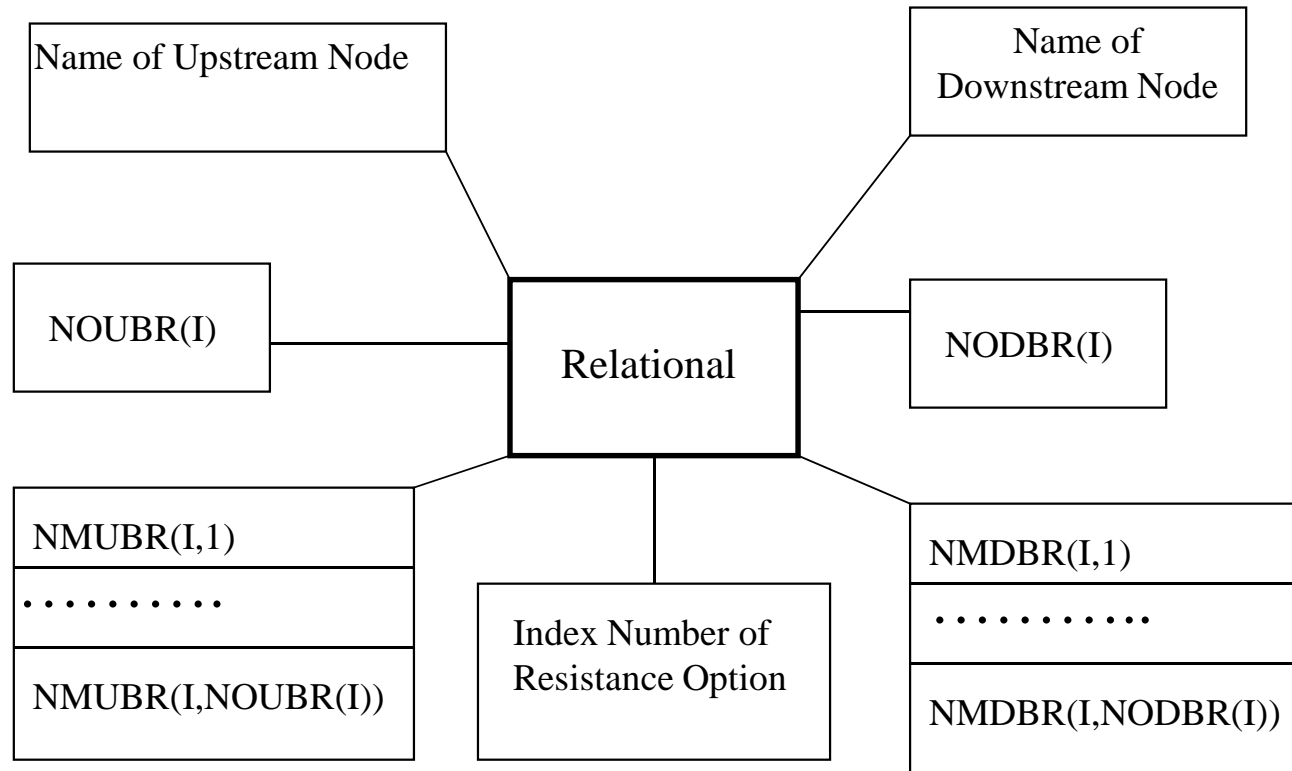
NAMEBR(I,3) = 51

NAMEBR(I,4) = 12

BRANCH PROPERTIES
GEOMETRIC -RELATIONAL

Name of Upstream Node		Name of Downstream Node

NOUBR(I)

Relational

NODBR(I)

NMUBR(I,1)
· · · · · · · · ·
NMUBR(I,NOUBR(I))

Index Number of Resistance Option

NMDBR(I,1)
· · · · · · · · · ·
NMDBR(I,NODBR(I))

NOUBR – Number of Upstream Branches

NMUBR – Name of Upstream Branches

NODBR – Number of Downstream Branches

NMDBR – Name of Downstream Branches

EXAMPLE OF BRANCH RELATIONAL PROPERTY

Relational Property of Branch 12
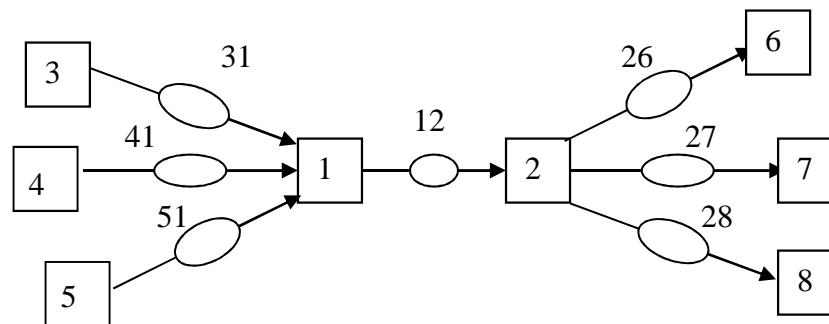
Name of Upstream Node, IBRUN(I) = 1

Number of Upstream Branches, NOUBR(I) = 3

Name of Upstream Branches,

NMUBR(I,1) = 31

NMUBR(I,2) = 41

NMUBR(I,3) = 51

Name of Downstream Node, IBRDN(I) = 2

Number of Downstream Branches, NODBR(I) = 3

Name of Downstream Branches,

NMDBR(I,1) = 26

NMDBR(I,2) = 27

NMDBR(I,3) = 28

Indexing Subroutine

SUBROUTINE INDEXI (NUMBER, NODE, NNODES, IPN)
or
SUBROUTINE INDEXI (NUMBER, IBRANCH, NBR, IB)

This subroutine determines the pointer of node or branch

Input Variables:
NUMBER: *Node* or *Branch* Number
NODE/IBRANCH: Array for storing *Node* or *Branch* Number
NNODES/NBR: Number of *Nodes* or *Branches*

Output Variable:
IPN/IB: Location of *Node* or *Branch* in Array (Pointer)

USE OF SUBROUTINE INDEXI

Location	1	2	3	*4*	5
NODE	100	200	300	*400*	500
INDEX	2	1	1	1	2
P	5125.50	4785.23	3876.45	2557.85	1668.25
TF	560.00	555.25	525.34	500.25	480.00

NNODE = 5

NINT = 3

Address location of a node (say node number 400).

```
NUMBER = 400
```
CALL INDEXI (NUMBER,NODE,NNODES,IPN)

In this Example IPN = 4

P(IP) = 2557.85

TF(IP) = 500.25

Example of a Typical User Subroutine

```fortran
C***********************************************************
      SUBROUTINE USRHCF(NUMBER,HCF)
C    PURPOSE: PROVIDE HEAT TRANSFER COEFFICIENT
C***********************************************************
      INCLUDE 'COMBLK.FOR'
C***********************************************************
      EQUIVALENCE (USRVAR1(1),HL)
      DATA FACTHC,CONHC,FNHC/1.0,0.15,0.33/
C    ESTIMATE HEAT TRANSFER COEFFICIENT IN ULLAGE NODES FROM FREE
C    CONVECTION CORRELATION
      NUMF=ICF(NUMBER)
      CALL INDEXI(NUMF,NODE,NNODES,IPN)
      NUMS=ICS(NUMBER)
      CALL INDEXS(NUMS,NODESL,NSOLIDX,IPSN)
      BETA=1./TF(IPN)
      DELTAT=ABS(TF(IPN)-TS(IPSN))
      GR=HL**3*RHO(IPN)**2*G*BETA*DELTAT/(EMU(IPN)**2)
      PRNDTL=CPNODE(IPN)*EMU(IPN)/CONDF(IPN)
      HCF=FACTHC*CONHC*CONDF(IPN)*(GR*PRNDTL)**FNHC/HL
      RETURN
      END
C***********************************************************
```

Compiling & Linking User Subroutine

User Prescribed Heat Transfer Coefficient

Diffuser

Liquid level at start of prepress

Liquid level at end of prepress
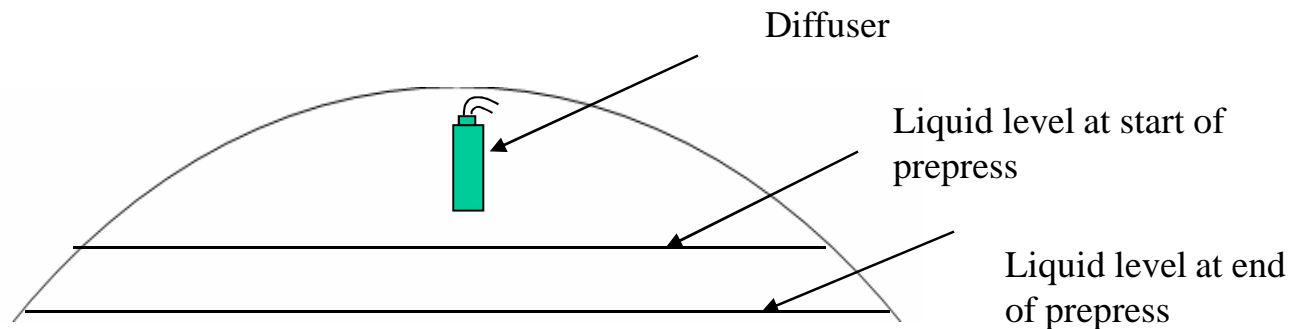
$$Nu = 0.15 \left(Gr \ \Pr \right)^{0.33}$$

$$Nu = \frac{hL}{k}$$

$$Gr = \frac{L^3 \rho^2 g \beta \Delta T}{\mu^2}$$

$$\Pr = \frac{C_p \mu}{k}$$

- In User Subroutine local property values are available in the common block

- Heat Transfer Coefficients are then calculated in SUBROUTINE USRHCF and returned to the SOLVER MODULE

User Subroutine to Calculate Heat Transfer Coefficient

```fortran
C***********************************************************
      SUBROUTINE USRHCF(NUMBER,HCF)
C    PURPOSE: PROVIDE HEAT TRANSFER COEFFICIENT
C***********************************************************
      INCLUDE 'COMBLK.FOR'
C***********************************************************
      EQUIVALENCE (USRVAR1(1),HL)
      DATA FACTHC,CONHC,FNHC/1.0,0.15,0.33/
C    ESTIMATE HEAT TRANSFER COEFFICIENT IN ULLAGE NODES FROM FREE
C    CONVECTION CORRELATION
      NUMF=ICF(NUMBER)
      CALL INDEXI(NUMF,NODE,NNODES,IPN)
      NUMS=ICS(NUMBER)
      CALL INDEXS(NUMS,NODESL,NSOLIDX,IPSN)
      BETA=1./TF(IPN)
      DELTAT=ABS(TF(IPN)-TS(IPSN))
      GR=HL**3*RHO(IPN)**2*G*BETA*DELTAT/(EMU(IPN)**2)
      PRNDTL=CPNODE(IPN)*EMU(IPN)/CONDF(IPN)
      HCF=FACTHC*CONHC*CONDF(IPN)*(GR*PRNDTL)**FNHC/HL
      RETURN
      END
C***********************************************************
```

SUMMARY

- User Subroutines can be used to add new capabilities that are not available to Users through Logical Options

- New capabilities may include:

  - Incorporating Design Specification; this may require iterative adjustment
  - User Specified Heat Transfer Coefficient
  - Incorporating a new physical model such as mass transfer
  - Customized output, Variable timestep etc.

- Checklist for User Subroutines

  - Identify subroutines that require modifications
  - Select GFSSP variables that require to be modified
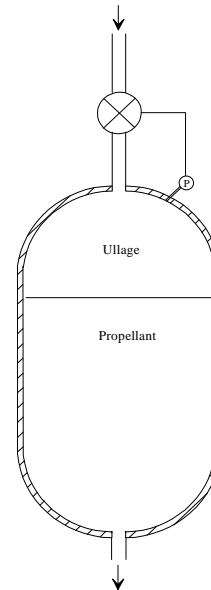 - Make use of GFSSP provided User variables in your coding

Advanced Options

1. Pressurization
2. Bang-Bang Control Valve
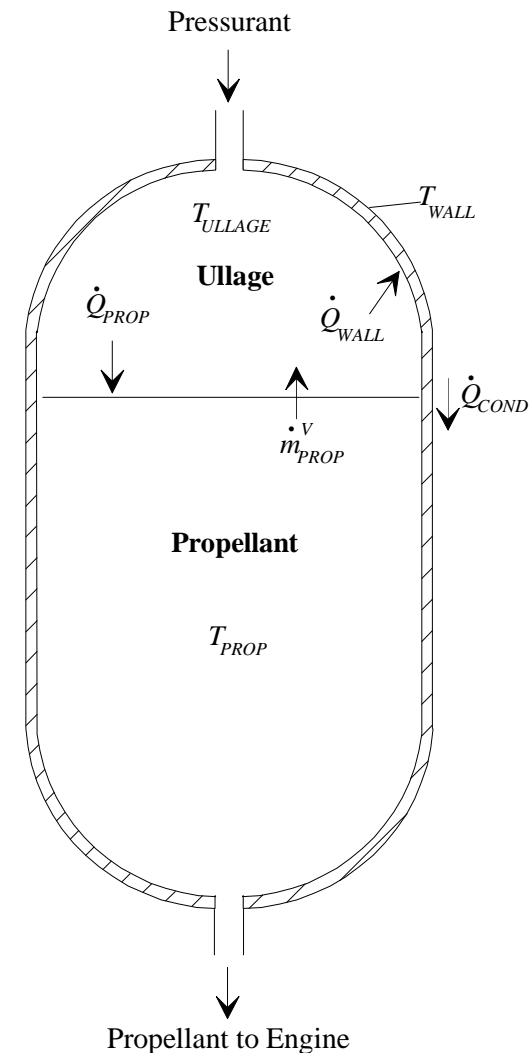3. Pressure Regulator
4. Flow Regulator

TANK PRESSURIZATION

TANK PRESSURIZATION

- Predict the ullage conditions considering heat and mass transfer between the propellant and the tank wall

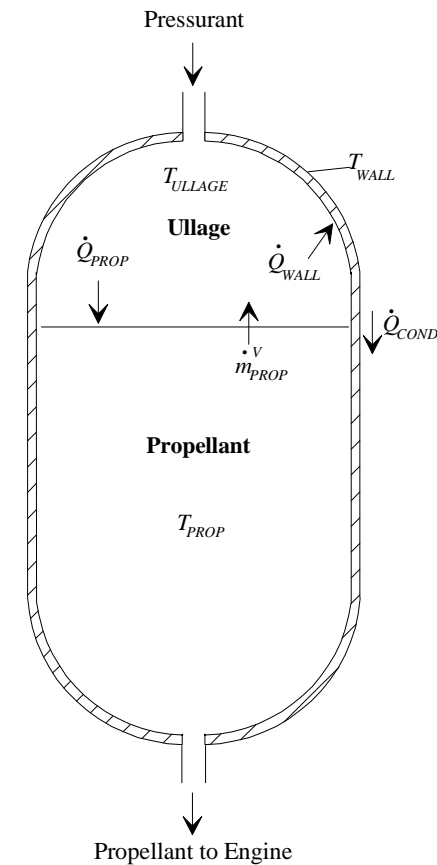- Predict the propellant conditions leaving the tank

Pressurant

T_{ULLAGE}

T_{WALL}

Ullage

$\dot{Q}_{PROP}$

$\dot{Q}_{WALL}$

$\dot{Q}_{COND}$

$\dot{m}^{V}_{PROP}$

Propellant

T_{PROP}

Propellant to Engine

TANK PRESSURIZATION

ADDITIONAL PHYSICAL PROCESSES

- Change in ullage and propellant volume.

- Change in gravitational head in the tank.

- Heat transfer from pressurant to propellant.

- Heat transfer from pressurant to the tank wall.

- Heat conduction between the pressurant exposed tank surface and the propellant exposed tank surface.

- Mass transfer between the pressurant and propellant.

Pressurant

T_{ULLAGE} T_{WALL}

Ullage

$\dot{Q}_{PROP}$ $\dot{Q}_{WALL}$ $\dot{Q}_{COND}$

$\dot{m}_{PROP} V$

Propellant

T_{PROP}

Propellant to Engine

TANK PRESSURIZATION
CALCULATION STEPS

For each time step calculate

- Ullage and Propellant Volumes

- Tank Bottom Pressure

- Heat Transfer between pressurant and propellant and pressurant and wall

- Wall Temperature

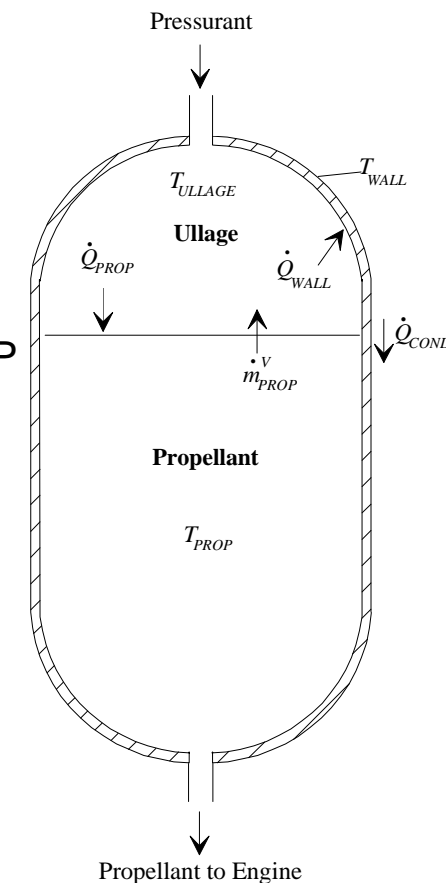- Mass Transfer from propellant to ullage
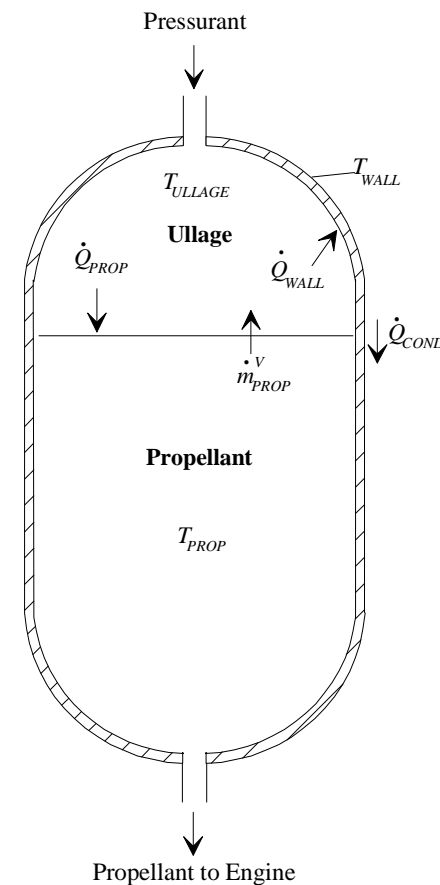
TANK PRESSURIZATION
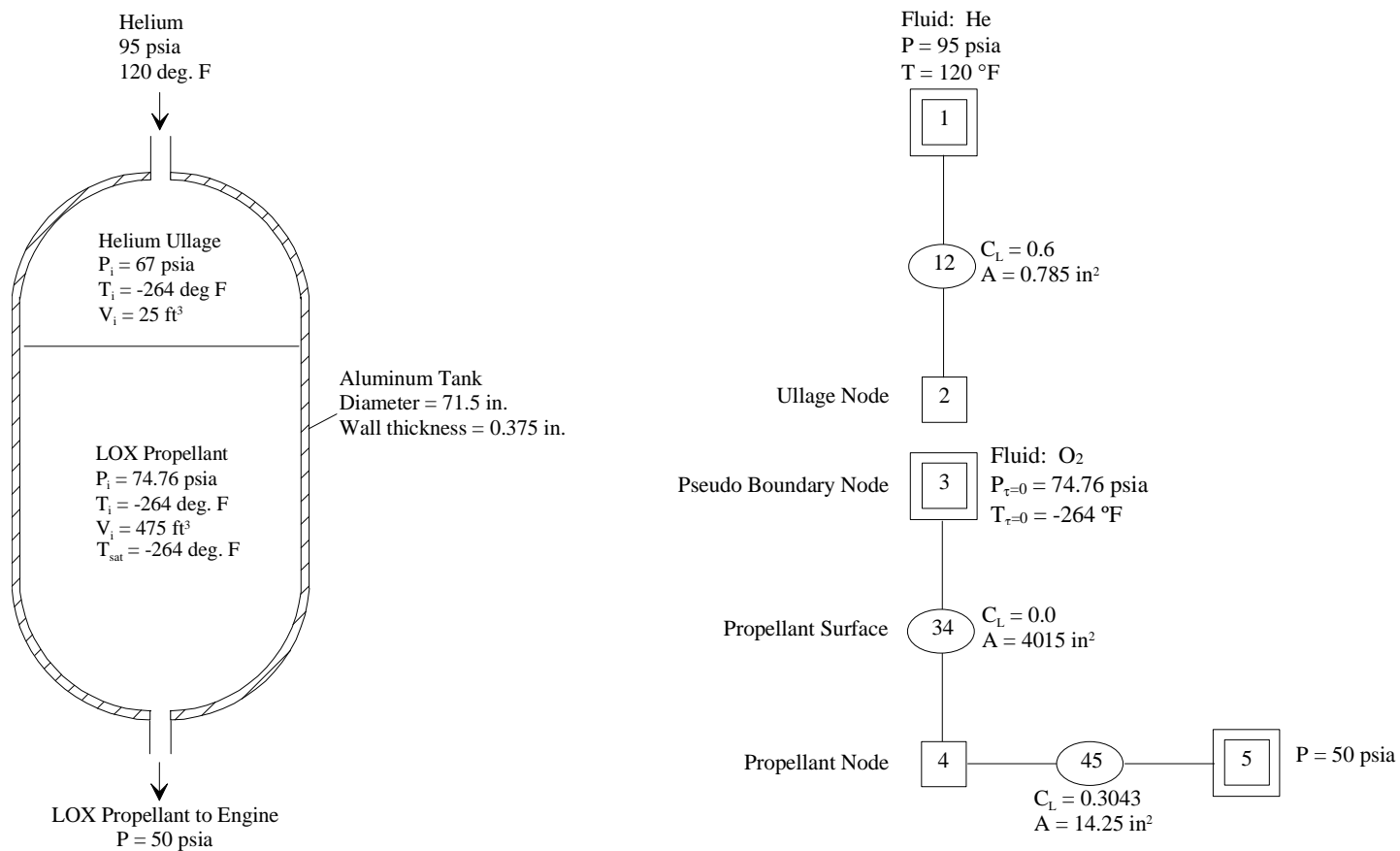## ADDITIONAL INPUT DATA FOR PRESSURIZATION

PRESS	Logical Variable to Activate the Option
NTANK	Number of Tanks in the Circuit
NODUL	Ullage Node
NODULB	Pseudo Boundary Node at interface
NODPRP	Propellant Node
IBRPRP	Branch number connecting NODULB & NODPRP
TNKAR	Tank Surface Area in Ullage at Start, in^2
TNKTH	Tank Thickness, in
TNKRHO	Tank Density, lbm/ft^3
TNKCP	Tank Specific Heat, Btu/lbm - R
TNKCON	Tank Thermal Conductivity, Btu/ft-sec-R
ARHC	Propellant Surface Area, in^2
FCTHC	Multiplying Factor in Heat Transfer Coefficient
TNKTM	Initial Tank Temperature, ^{o}F

Pressurant

T_{ULLAGE} T_{WALL}

Ullage

$\dot{Q}_{PROP}$ $\dot{Q}_{WALL}$ $\dot{Q}_{COND}$

$\dot{m}_{PROP}^V$

Propellant

T_{PROP}

Propellant to Engine

TANK PRESSURIZATION
EXAMPLE 10 TANK SCHEMATIC AND GFSSP MODEL

Helium
95 psia
120 deg. F

Helium Ullage
P_i = 67 psia
T_i = -264 deg F
V_i = 25 ft^3

Aluminum Tank
Diameter = 71.5 in.
Wall thickness = 0.375 in.

LOX Propellant
P_i = 74.76 psia
T_i = -264 deg. F
V_i = 475 ft^3
T_{sat} = -264 deg. F

LOX Propellant to Engine
P = 50 psia

Fluid: He
P = 95 psia
T = 120 °F

1

C_L = 0.6
12   A = 0.785 in^2

Ullage Node   2

Pseudo Boundary Node   3   Fluid: O_2
$P_{\tau=0}$ = 74.76 psia
$T_{\tau=0}$ = -264 °F

Propellant Surface   34 C_L = 0.0
A = 4015 in^2

Propellant Node   4   45   5   P = 50 psia
C_L = 0.3043
A = 14.25 in^2

TANK PRESSURIZATION
EXAMPLE 10 PRESSURIZATION INPUT

```
 NODE   PRES (PSI)   TEMP(DEGF)   MASS SOURC   HEAT SOURC   THRST AREA   VOLUME       CONCENTRATION
    2  0.6700E+02  -0.2640E+03  0.0000E+00  0.0000E+00  0.0000E+00  0.4320E+05 1.0000 0.0000
    4  0.7476E+02  -0.2640E+03  0.0000E+00  0.0000E+00  0.0000E+00  0.8208E+06 0.0000 1.0000
ex10h1.dat
ex10h3.dat
ex10h5.dat
                                        .
                                        .
                                        .

NUMBER OF TANKS IN THE CIRCUIT
     1

NODUL NODULB NODPRP IBRPRP TNKAR TNKTH TNKRHOTNKCP TNKCON ARHC FCTHC TNKTM
    2     3     4     34 6431.91  0.375 170.00  0.20 0.0362 4015.00  1.00 -264.00
 NODE DATA FILE
FNODE.DAT
 BRANCH DATA FILE
FBRANCH.DAT
```

Tank Input Units
VOLUME, in^3
TNKAR, in^2
TNKTH, in
TNKRHO, lbm/ft^3
TNKCP, Btu/lbm-R
TNKCON, Btu/ft-s-R
ARHC, in^2
TNKTM, deg. F

TANK PRESSURIZATION
EXAMPLE 10 PRESSURIZATION OUTPUT

```
SOLUTION
INTERNAL NODES
    NODE     P(PSI)        TF(F)         Z          RHO        EM(LBM)     CONC
                                                 (LBM/FT^3)

                                                                        HE         O2
      2    0.9138E+02 -0.1347E+03  0.1006E+01  0.1047E+00  0.5144E+01  0.9690E+00  0.0310
      4    0.9869E+02 -0.2640E+03  0.2310E-01  0.6514E+02  0.2937E+05  0.0000E+00  1.0000


BRANCHES
BRANCH  KFACTOR           DELP     FLOW RATE    VELOCITY    REYN. NO.   MACH NO. ENTROPY GEN. LOST WORK
 (LBF-S^2/(LBM-FT)^2) (PSI)   (LBM/SEC)   (FT/SEC)                              BTU/(R-SEC)  LBF-FT/SEC
12    0.238E+05      0.362E+01   0.148E+00   0.445E+03  0.156E+06  0.129E+00  0.281E-02  0.127E+04
34    0.000E+00      0.000E+00   0.163E+03   0.899E-01  0.412E+06  0.114E-03  0.000E+00  0.000E+00
45    0.263E+00      0.487E+02   0.163E+03   0.253E+02  0.690E+07  0.323E-01  0.115E+00  0.176E+05


    NUMBER OF PRESSURIZATION SYSTEMS =   1
  NODUL    NODPRP    QULPRP      QULWAL       QCOND      TNKTM       VOLPROP       VOLULG
     2        4      1.9642      8.5069      0.0022    196.4447    450.8641      49.1359



   SOLUTION SATISFIED CONVERGENCE CRITERION OF     0.100E-02 IN   5 ITERATIONS
TAU =      10.0000    ISTEP =           100
```
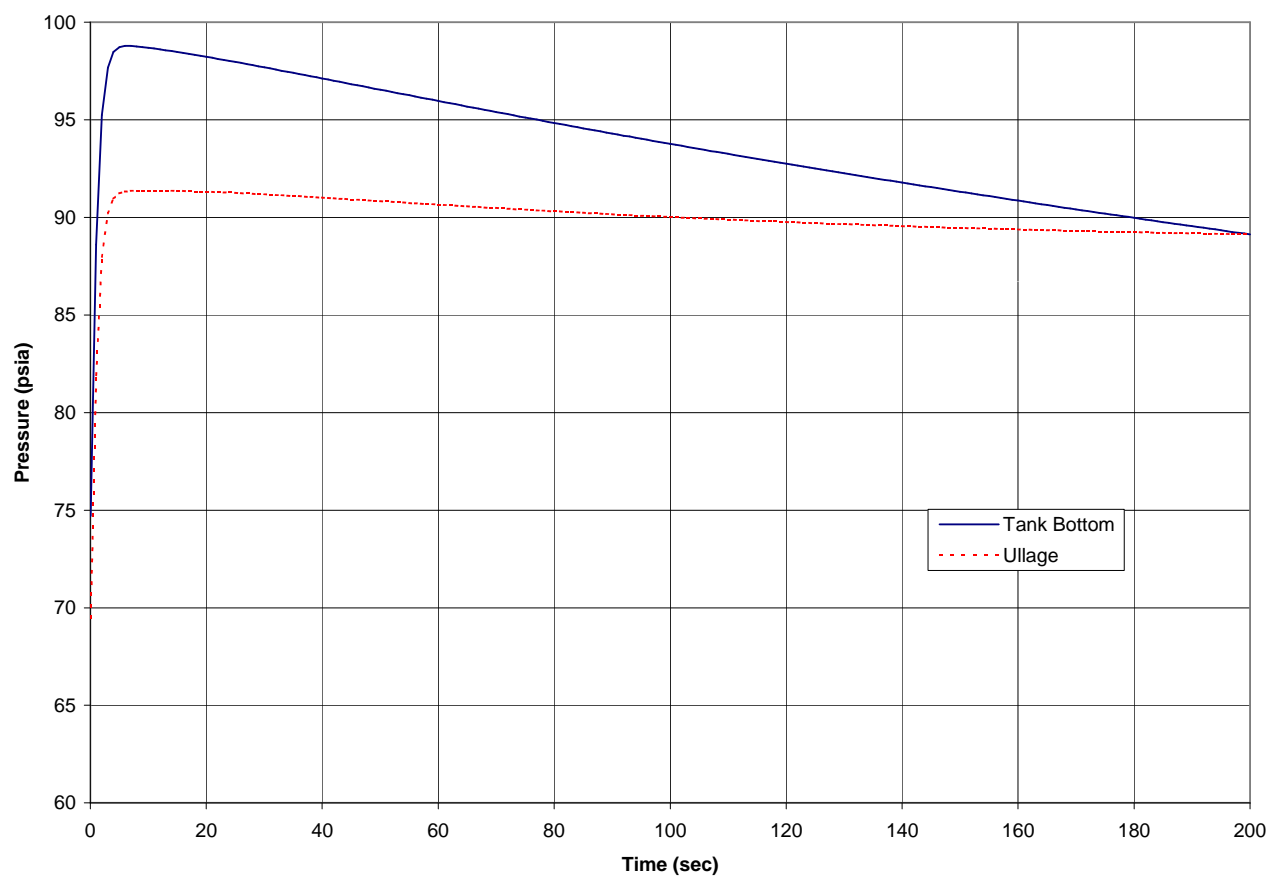
Tank Output Units
QULPROP, Btu/s
QULWAL, Btu/s
QCOND, Btu/s
TNKTM, deg. R
VOLPROP, ft^3
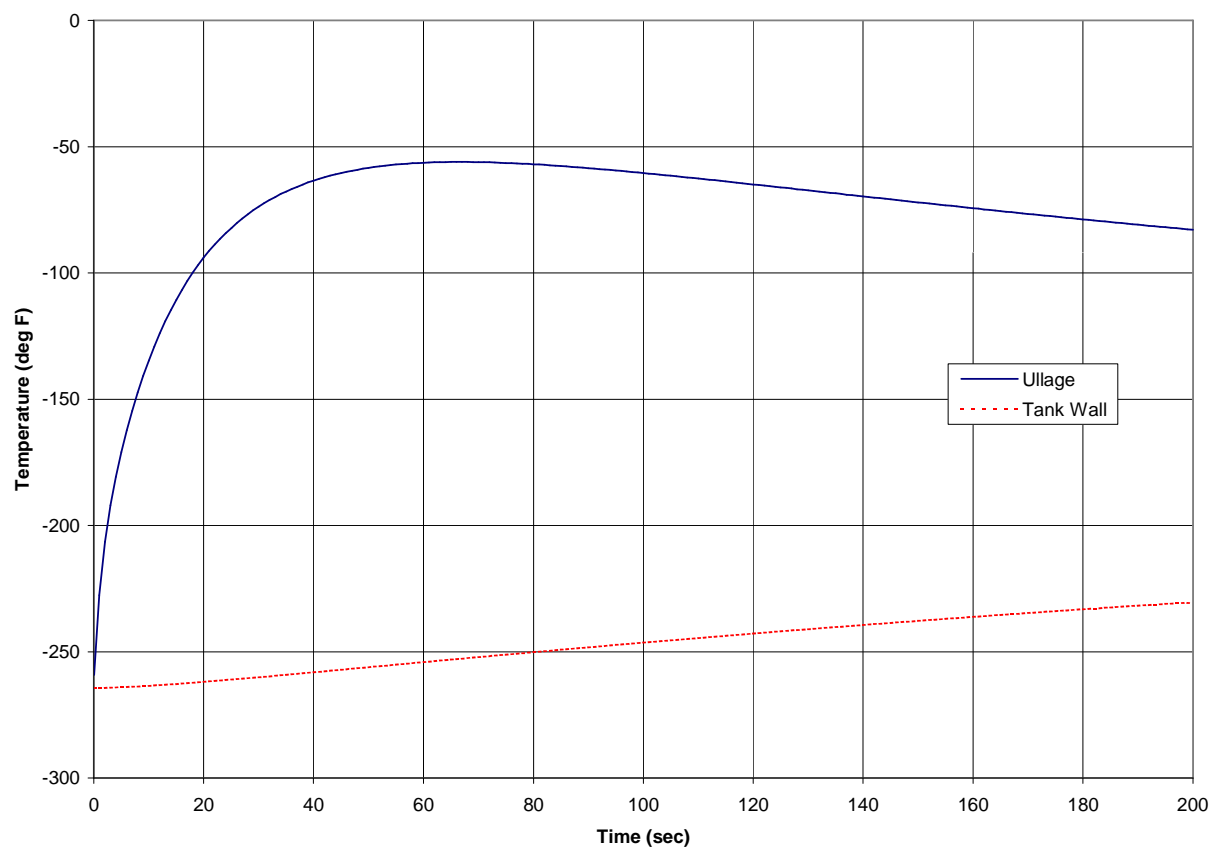VOLULG, ft^3

TANK PRESSURIZATION
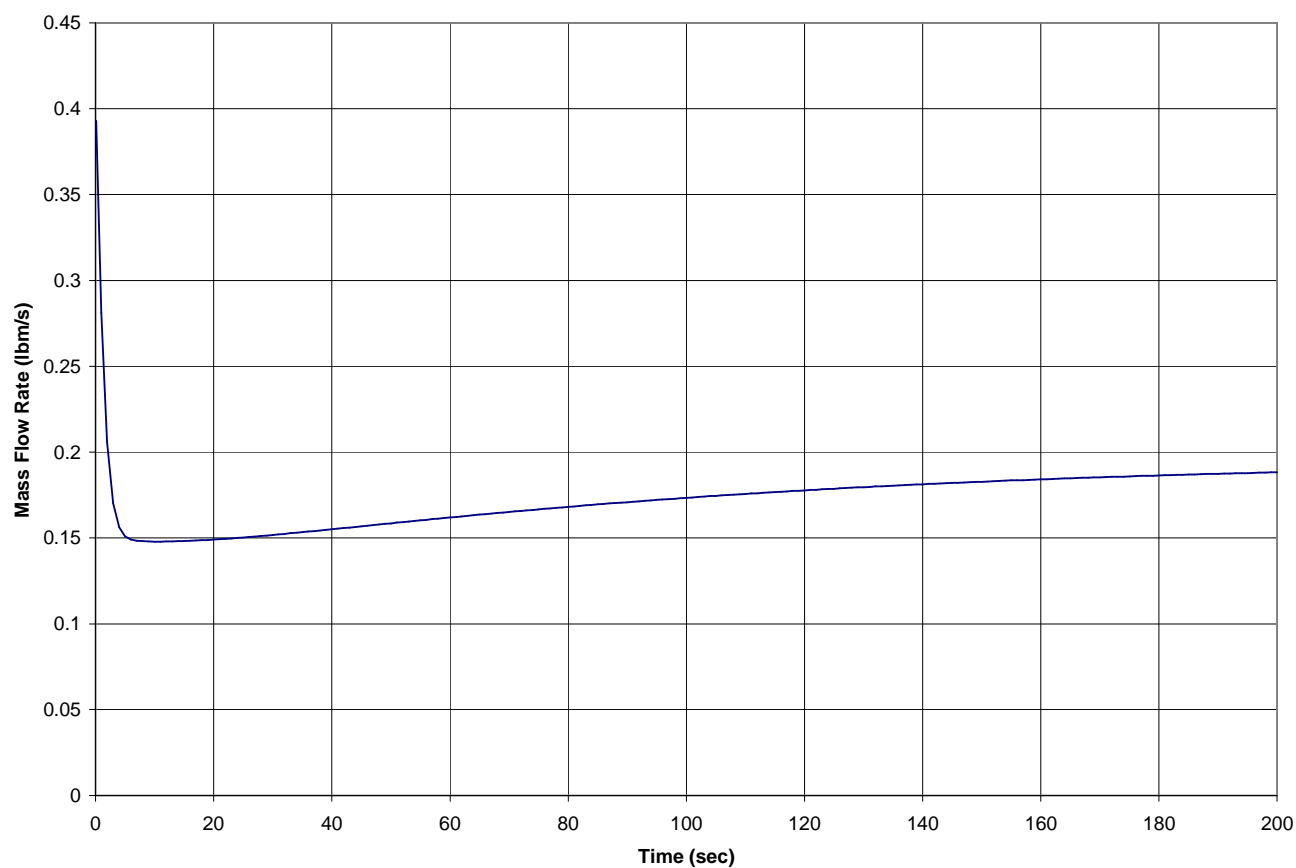## EXAMPLE 10 ULLAGE AND TANK BOTTOM PRESSURE HISTORY

TANK PRESSURIZATION
EXAMPLE 10 ULLAGE AND TANK WALL TEMPERATURE HISTORY

TANK PRESSURIZATION
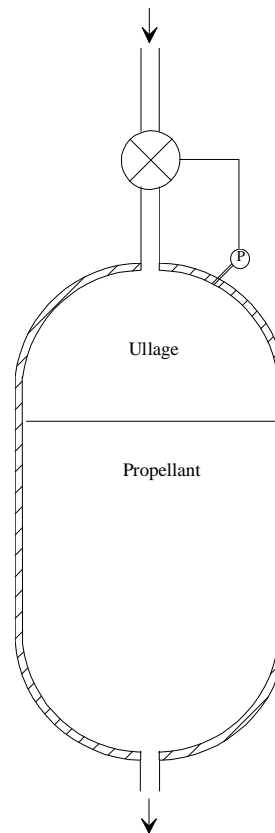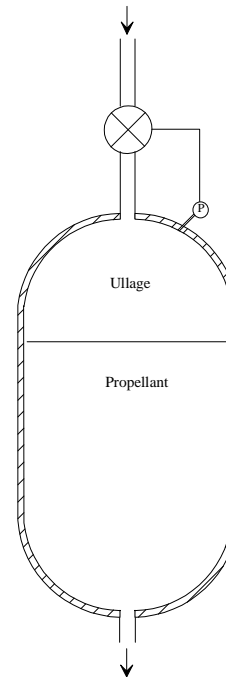## EXAMPLE 10 HELIUM FLOW RATE HISTORY

Demonstration of:
1. Bang Bang Control Valve
2. Pressure Regulator
3. Flow Regulator

Tutorial – 3
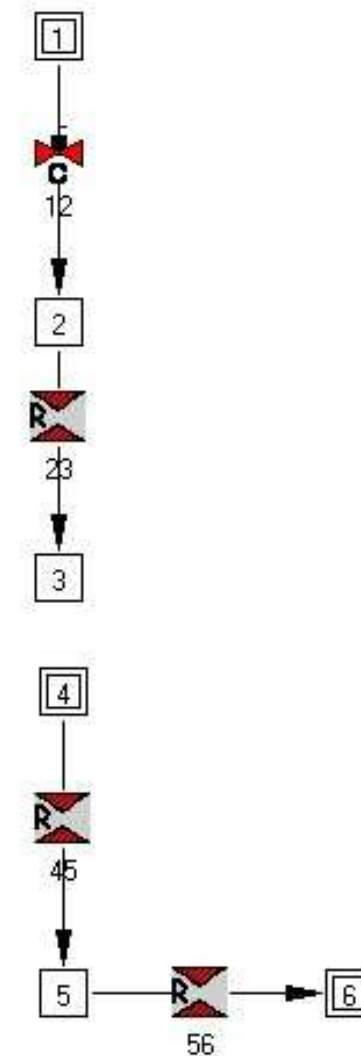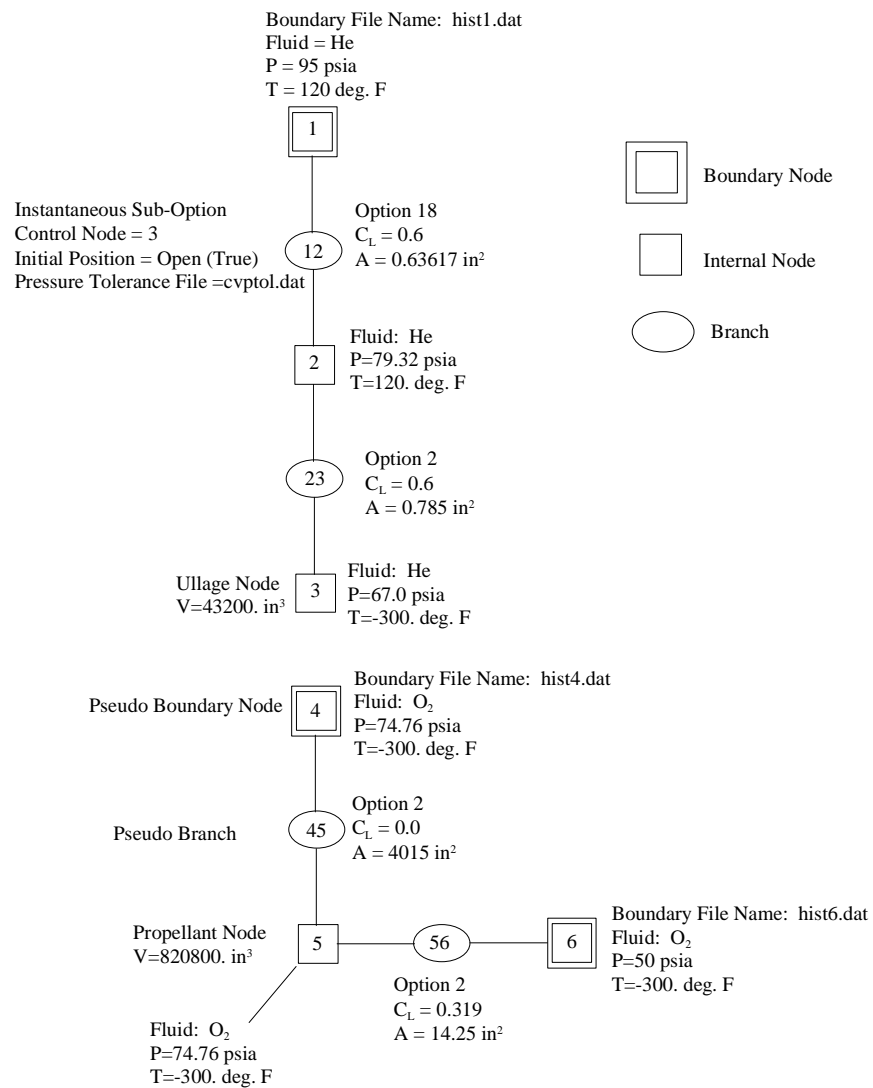# Valve-Controlled Pressurization of a Propellant Tank

Problem Elements:

- Control tank pressure within a specified tolerance

- Use control valve branch option

- Use tank pressurization advanced option
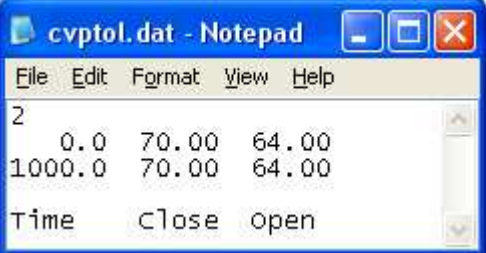
- Use 2 fluids (oxygen and helium)

Discretization and Boundary Conditions

Boundary File Name: hist1.dat
Fluid = He
P = 95 psia
T = 120 deg. F

[1]

Instantaneous Sub-Option
Control Node = 3
Initial Position = Open (True)
Pressure Tolerance File =cvptol.dat

(12) Option 18
$C_L = 0.6$
$A = 0.63617$ in^2

[2] Fluid: He
P=79.32 psia
T=120. deg. F

(23) Option 2
$C_L = 0.6$
$A = 0.785$ in^2

Ullage Node
V=43200. in^3
[3] Fluid: He
P=67.0 psia
T=-300. deg. F

Pseudo Boundary Node
[4] Boundary File Name: hist4.dat
Fluid: O$_2$
P=74.76 psia
T=-300. deg. F

Pseudo Branch
(45) Option 2
$C_L = 0.0$
$A = 4015$ in^2

Propellant Node
V=820800. in^3
[5] (56) [6] Boundary File Name: hist6.dat
Fluid: O$_2$
P=50 psia
T=-300. deg. F

Option 2
$C_L = 0.319$
$A = 14.25$ in^2

Fluid: O$_2$
P=74.76 psia
T=-300. deg. F

[ ] Boundary Node

[ ] Internal Node

( ) Branch

Suggested Steps

- Fill in Edit/Options

  - Conv. Crit. = 0.005; RELAXK = 0.5

  - Time step = 0.1 s; run duration = 200 s

  - Check <u>Tank Pressurization</u> unsteady option

  - Select two fluids: Oxygen and Helium (Note which one is selected first)

- Construct Schematic

  - There will be 3 boundary node history files (hist1.dat, hist4.dat, hist6.dat)

  - Don't forget:

  - Supply tank volumes to nodes 3 and 5

  - Supply P, T, and <u>species fraction</u>

  - Control Valve (branch 12) will require a pressure tolerance file:

  - Control Valve is controlled by pressure in node 3

- Fill out the Advanced/Tank Pressurization form (next slide)

cvptol.dat - Notepad

```
2
   0.0   70.00   64.00
1000.0   70.00   64.00
```

Time   Close   Open

Tank Pressurization Option

Cylindrical aluminum tank

Density: 170. lbm/ft^3

Specific Heat: 0.2 Btu/lbm-R

Thermal Conductivity: 0.0362 Btu/ft-s-R

Wall Thickness: 0.375 in.

Tank Surface Area: 6431.91 in^2

Ullage/Propellant Heat Transfer Area: 4015. in^2

T_{tank}: -300. °F

Conv. Heat Transfer Adj. Factor: 1.0

Use default heat transfer correlation coefficients

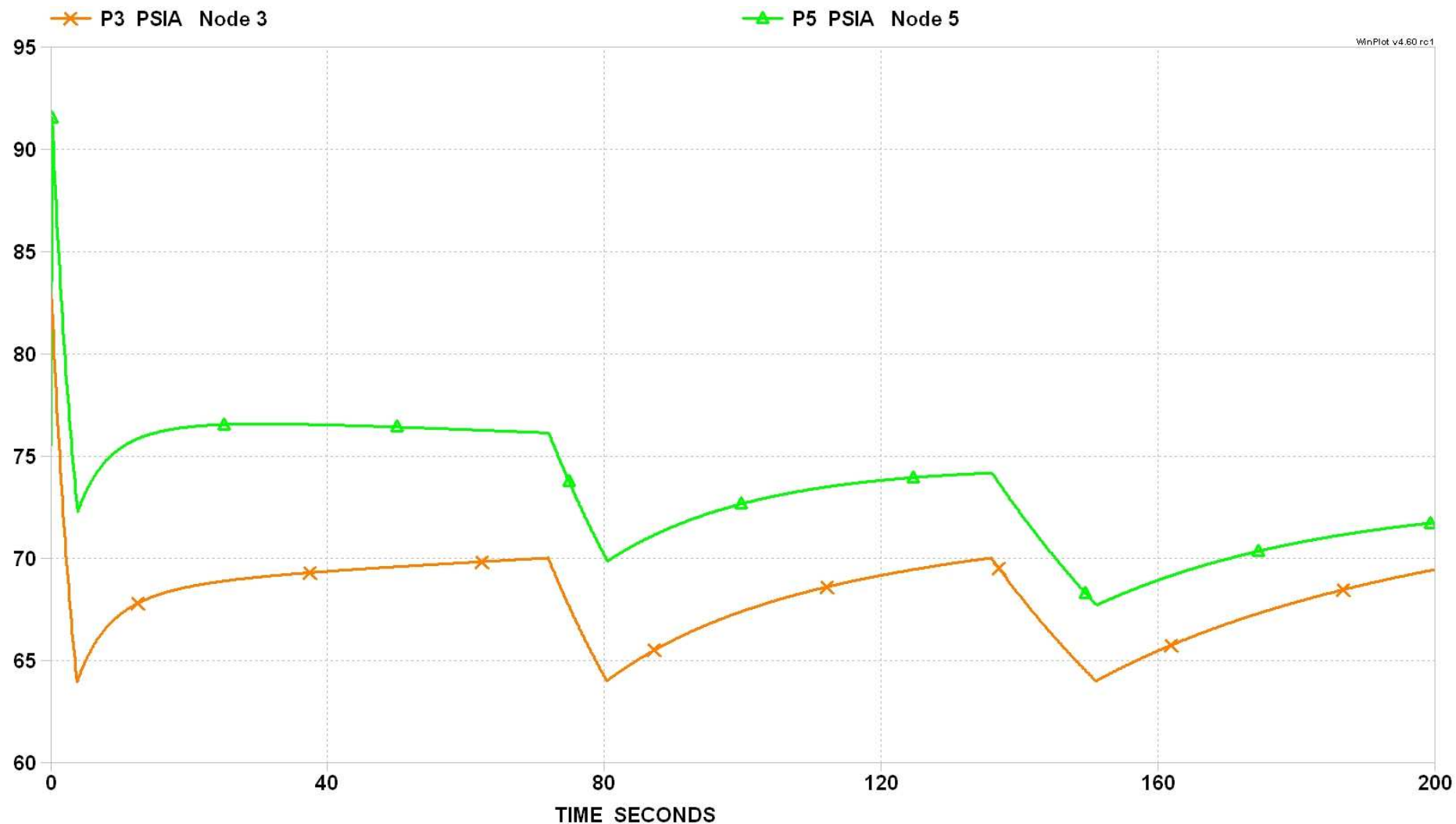Don't forget to click ACCEPT before closing

Study of the Results

- Study *tut3.out* and *plot files* to note the following facts:
  - Ullage pressure is maintained between 64 and 70 psia by the control valve
  - Difference between ullage pressure and tank bottom pressure due to gravitational head
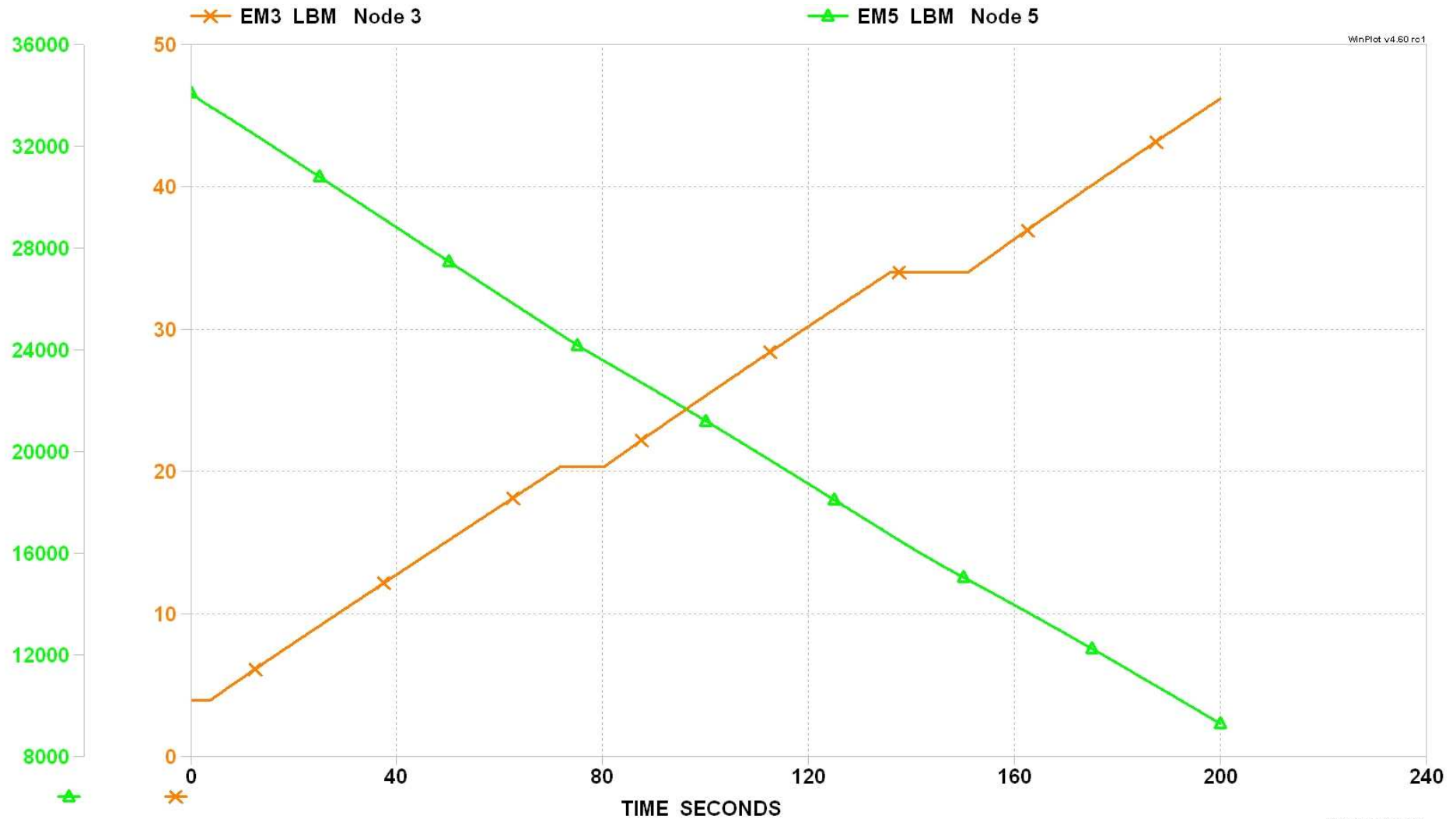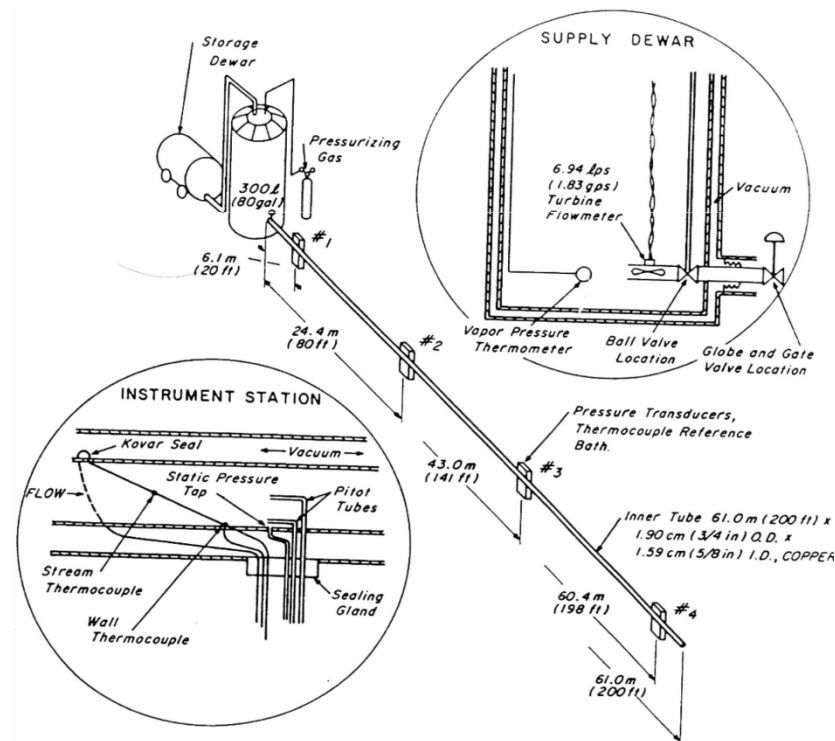 - Tank bottom pressure decreases as propellant is expelled from the tank

Tutorial – 4
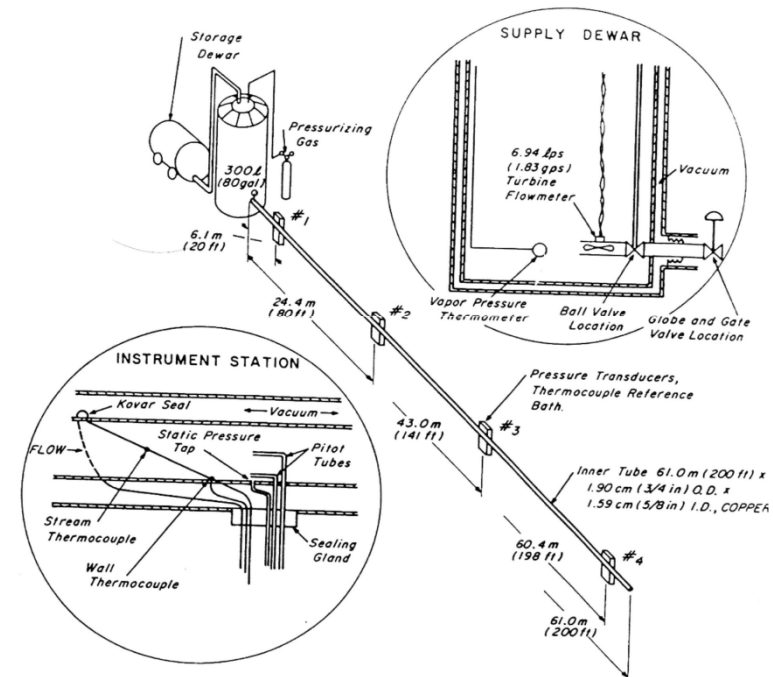# CHILLDOWN OF CRYOGENIC TRANSFER LINE

CHILLDOWN OF TRANSFER LINE SCHEMATIC

Problem Considered:

•Time dependent Pressure, Temperature and Flow rate history during chilldown

Model Details

Mass of Pipe = 65 lbs

Material: Stainless Steel 304

Length of the pipe = 200 feet

Inside Diameter = 0.625 inches

Inlet Condition (LH2): 75 psia, -411 Deg F
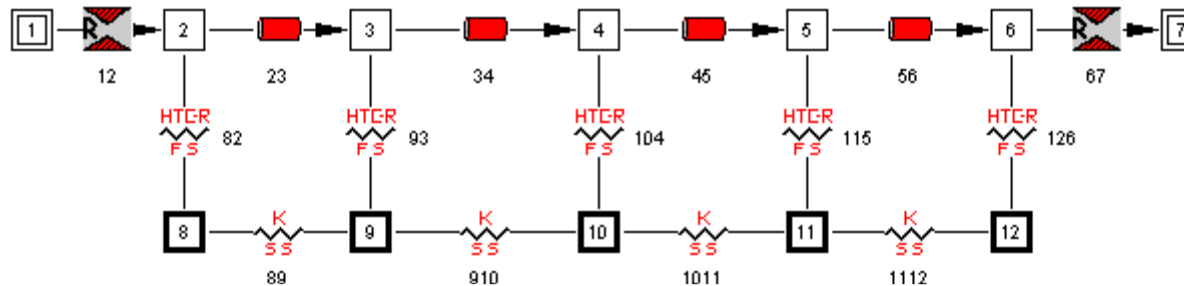
Exit Condition: 12.05 psia

Initial Condition : 12.05 psia, 44.33 Deg F

Inlet Valve : Area = 0.3068, Cd= 0.6

Outlet Valve : Area = 0.3068, Cd= 1.0

GFSSP Model

Use a timestep of 0.0015 sec

Run the model for 100 seconds

STUDY OF THE RESULTS

- Plot pressure, flowrate and fluid and solid temperature history
- Estimate the predicted chilldown time
- Observe the phase change behavior